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BY

FRANK M. SWARTZ

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Subsurface Projection of Cambro-Ordovician Sediments in the Pennsylvania-New York Region, And Relation to Oil and Gas Possibilities

By Frank M. Swartz*

Introduction

Prospective further decline in oil and gas production from the Devonian and Carboniferous sands that have afforded the supplies so far discovered in Pennsylvania, lends increased importance to possibilities of geologically older horizons despite their greater depth and lack of production in the few wells that have so far reached them in the State.

Active interest in possibilities of the older horizons is evidenced by drilling now in progress near Bedford in south-central Pennsylvania, as well as by recent completion of the deep Hockenberry test north of Pittsburgh. (See Figure 1.) Concern with the deep formations also led the Pittsburgh Geological Society to sponsor, in 1947, a symposium on the Trenton and Sub-Trenton of the Northern Portion of the Appalachian Basin.

The present paper has been developed from parts of the symposium, as published in 1948 in the Bulletin of the American Association of Petroleum Geologists. Liberal use has been made of subsurface data and conclusions presented by Fettke (1948) and Cohee (1948), in order to broaden and strengthen the geological interpretations based on surface information summarized by the writer. (Swartz, 1948.)

Scope and Method

The Cambrian and Ordovician sediments discussed on following pages occur at depth in western Pennsylvania and elsewhere through the northern portion of the Appalachian structural basin. The areas of subsurface extension are delimited in Figure 2 by the bordering belts of outcrop where the Cambrian and Ordovician strata rise to ground level.

Stratigraphic studies along the marginal belts of exposure, supplemented by data from the few deep test wells, give insight into regional characters of the sediments, so that trends in facies and in thickness changes, and variations in history of burial and tectonics, can be projected into the areas of subsurface occurrence and used in interpreting petroleum source-bed and reservoir possibilities.

The Cambrian and Ordovician strata of the province show by their fossils, compositions, and structures that they originated as sediments spread on the floors and along marginal areas of ancient, shallow seas that for long periods varyingly inundated a comparatively level, gradually subsiding platform region. At times, easterly lands were uplifted, and suffered weathering and erosion, so that sands and clays worn from their surfaces were transported to the Pennsylvania region and were there deposited in deltas, lagoons, and estuaries as well as in more open portions of the sea waters. At times, sands were brought in from the northwest and north rather than from the southeast, markedly affecting the patterns of distribution.

During long intervals of Cambrian and Ordovician time, the neighboring lands were low, or small and distant, so that little detritus from them reached the platform of sedimentation. During these intervals, deposits of calcium carbonate tended to accumulate on the sea floor, in part as a chalky flocculate precipitated because of lowered concentration of dissolved carbon dioxide, in lesser part as shells and skeletons secreted by sea animals and plants. Locally, magnesium of the sea waters reacted with the limy sediments, forming dolomites in a fashion imperfectly understood.

The seas repeatedly were modified in geographic pattern and distribution. At times the waters withdrew from much or all of the region, and the exposed sediments formed in preceding stages of sea deposition were then laid bare to weathering, rain wash, stream erosion, and the solvent action of circulating ground waters.

Although the platform of sedimentation was comparatively level, there were irregularities both of subsidence and emergence. The form of the surface of sedimentation, and likewise curvatures of sedimentary layers increasingly buried below younger deposits, were progressively modified by differential warping and by regional variations in thickness of concurrently accumulating sediments. Smaller scale, incipient arching that is not well substantiated may have caused local shoaling of the sea floor, and during intervals of emergence may locally have affected surface elevations.

It follows from these relationships that the characters of sedimentary strata, and the manner in which they change from one area to another, not only give evidence of the geography of their sedimentation, but can in turn be better understood and their trends projected to new regions as soon as the broad geographic outlines are made apparent. This is the basic concept of the present investigation. Employing knowledge of the sediments at the surface and subsurface, with age correlations obtained from distinctive fossil faunas and from lithologic tracing and interfingering, the broad regional features of each of successive major subdivisions of the Cambrian and Ordovician sediments are discussed, and are illustrated by isopachous and isolithic maps. Interpretations of the geography of sedimentation are implicit in each of these discussions, but have not been fully developed for the present account of the study.

A number of basic factors are common to oil and gas problems of all parts of the Cambrian-Ordovician sequence, and affect the manner in which data are arranged to build up preliminary opinions about possibilities of each of the constituent subdivisions of the rock succession. Attention accordingly is first devoted to brief review of premises about the nature of petroleum source beds and reservoirs, and relationships to the ancient geographies of sedimentation and to the post-depositional history.

Acknowledgments

The present paper represents continuation of studies discussed (Swartz, 1948) in the Trenton and Sub-Trenton symposium recently published by the American Association of Petroleum Geologists. Liberal use has been made of the contributions there furnished by Fettke (1948) and by Cohee (1948). The work has been jointly sponsored by the Pennsylvania Topographic and Geologic Survey and by the Mineral Industries Experiment Station of The Pennsylvania State College. Information on subsurface features of the Upper Ordovician Oswego sandstone was originally assembled with support of the Quaker State Oil Refining Corporation and Bradley Producing Corporation, and is here made available through the kind permission of the responsible officers.

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Order of Discussion

The discussions presented on following pages are summaries intended to be helpful as attention is devoted to the following problems: What are the regional characters and facies inter-relationships of sediments of each of major subdivisions of the Cambrian and Ordovician strata of the Pennsylvania-New York-Ohio region? What were the general conditions and geographies of sedimentation? Were there periods of widespread emergence? What sediments have promise as possible petroleum source beds? Where and at what horizons did sediments accumulate with regional porosites of reservoir type? Did leaching and reworking significantly modify porosity patterns? Did oil and gas move into early-stage reservoirs whose locations affected possibilities of subsequent loci of accumulation? Were reservoir conditions and migration possibilities altered as Paleozoic sedimentation continued? Did Late Paleozoic Appalachian deformation cause serious dispersion of oil and gas theretofore accumulated in the sediments and if so, where?

A number of basic factors and premises are common to oil and gas problems of all parts of the Cambro-Ordovician sequence, and affect the manner in which data are arranged to build up preliminary opinions about possibilities of each of the constituent subdivisions of the rock succession. Attention accordingly is first devoted to brief review of pertinent suppositions about nature of petroleum source beds and reservoirs, and their relation of paleogeography of sedimentation and to post-depositional history; there then follow summaries of regional characters of successive major subdivisions of the Cambrian and Ordovician of the Pennsylvania-New York-Ohio region; coupled in each case with preliminary attempts to evaluate oil and gas possibilities. It must be emphasized that the remarks here offered are suggestive only, and are by no means intended to serve as full and final analyses of the difficult and complex problems that challenge geologists of the region.

Premises About Petroleum Source Beds And Reservoirs, In Relation To Paleogeography of Sedimentation of the Cambro-Ordovician Strata

Interpretation of oil and gas possibilities on the basis of regional trends of sediments, involves suppositions about types of deposits that have served as petroleum source beds and reservoirs, and about their relations to the ancient geographies of sedimentation.

Although opinions about source sediments vary in detail, there seems to be general agreement that special promise is offered by marine near-shore, and associated brackish-water estuarine-lagoonal suites of clays and sands. Rich petroleum occurrences in marine dolomites and limestones suggest that such carbonates likewise have entombed organic materials of favorable parent types; though like the detritals, the carbonate sediments doubtlessly have accumulated under conditions varying widely in balance between growth, destruction, and burial of organic matter. Fresh-water river sediments evidently afford no possibilities as petroleum source beds, and there is doubt that even the fresh-water lake-shales that yield oil by distillation have actually given rise to natural petroleum.

In the shallow-water suites of marine and estuarine detritals, sands cleansed by vigorous surf and current agitation in exposed beaches and bars suffer loss of source substances of petroleum. After burial, however, their well-bridged interstices resist destruction by compaction, and where not closed by cements furnish potential reservoir porosities wherever structures or permeability wedge-outs are favorable.

The carbonate sediments also offer some reservoir possibilities associated with original as contrasted with secondary openings. Deposits of shelly materials and of reef-growths may locally have been honeycombed with crevices, and fragmented shell-sands likewise should have been porous in early stages of their history. However, the effective reservoir pores of the carbonate sediments are likely to have been much affected by secondary modifications, and in many instances may be wholly secondary in origin.

The Cambro-Ordovician sediments of Pennsylvania and adjacent states include thick sequences both of shallow-water marine - estuarine - lagoonal clays and sands, and of marine carbonates, that in general nature resemble proved petroliferous sequences of other regions of the world. Stratigraphic-paleogeographic studies can be helpful in outlining distributions of sedimentary types in terms of the near-shore and offshore regions of the ancient geographies of accumulation, as well as by giving insight into possible horizons of emergence and leaching, and into possible effects of burial and deformation.

Reservoir Possibilities In Relation To The Post-Depositional History Of the Sediments

Reservoir conditions of the Cambro-Ordovician sediments of the Appalachian region were affected in complex ways by post-depositional events, and the reservoir conditions doubtless passed through several successive, changing stages. Brief consideration will be given to some of these post-depositional relationships under the following sub-headings: Possible reservoirs of leaching associated with surfaces of unconformity; Reservoir porosities in relation to time of entry of oil and gas and to possible complexities of tilting and migration; Reservoir and petroleum possibilities in relation to deep burial and to rock deformation.

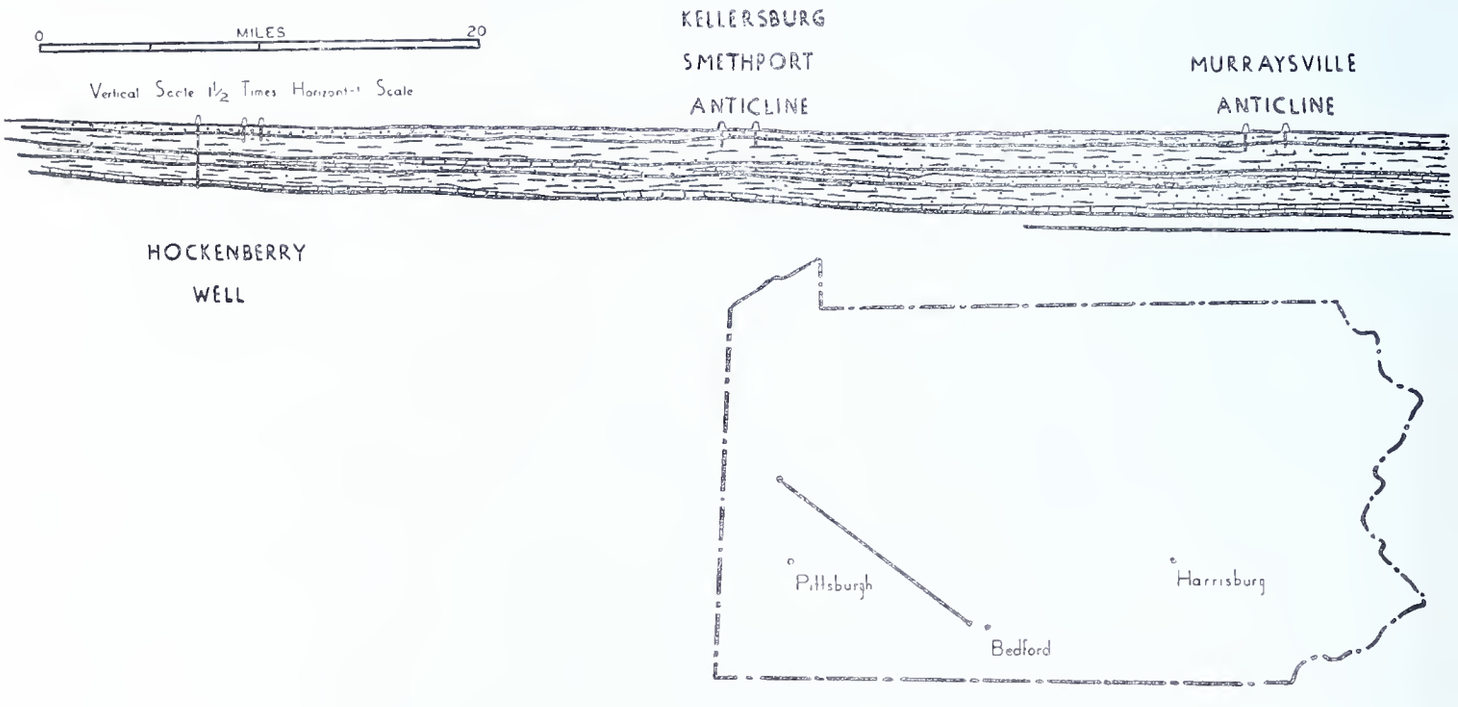


Figure 1 — General stratigraphy and structure in southwestern Pennsylvania along the line from the Hockenberry well in westcentral Pennsylvania (see Fettke, 1948), to locations of test wells now being drilled at the Schellsburg dome west of Bedford.

Possible Reservoirs of Leaching Associated with Surfaces of Unconformity

Sedimentation was by no means fully continuous in the northern Appalachian region during Cambro-Ordovician time. Progressive shrinkage of areas of sedimentation is especially marked in the successive Upper Cambrian—Lower Ordovician — Middle Ordovician Chazyan stages of deposition.

In the areas and at the times that carbonate beds and carbonate-rich quartz sands were uncovered by shifts in margins of the ancient seas, solution and leaching must have taken place. Extent, rate, and total effect of the solvent activity varied with composition of the emergent materials, height above water table, and nature of climate.

Processes of several, somewhat different types favor development of porous zones in such emergent strata. In limestones and dolomites, solution tends to enlarge crevices, and to produce sink holes and subsurface openings, augmented by fractures where slumping is extensive. Where carbonate-rich sands are exposed, leaching in place increases porosity by removal of carbonate cement clogging interstices, and transportation and redeposition of the weathered quartz sand may form new and porous lenses. All of these types of openings would furnish potential reservoir porosities if and when renewed sedimentation laid down suitable cap-rock strata.

In the Cambro-Ordovician sediments of the Pennsylvania region, geographies of Beekmantown and Chazyan stages suggest that both solution in exposed limestones and dolomites, and leaching and reworking of Upper Cambrian sandy layers, could have been fairly extensive. The surfaces of unconformity deserve attention in future exploration.

Reservoir Porosities in Relation to Time of Entry of Oil and Gas, and to Possible Complexities of Tilting and Migration

Time of entry of oil and gas into the Cambro-Ordovician reservoir horizons, plausibly was a significant factor affecting the nature, distribution, and maintenance of the effective reservoir porosities.

The increasing weight of overburden that resulted from continued Paleozoic sedimentation, subjected the buried Cambro-Ordovician strata to a tightening, natural wringer that compacted especially the weaker layers and thus tended to drive out the contained fluids. The less competent source beds may have yielded considerable proportions of their potential oil and gas as well as a large part of their interstitial water, after burial under several thousand feet of sediment.

Because of wide spreading of the sedimentary materials, the rate of accretion in thickness was comparatively gradual on the Appalachian platform during Paleozoic time. Consequently, initiation of migration from source beds may have been somewhat delayed in comparison, for example, with movements in the more rapidly deposited Tertiary sediments of the Gulf Coast region of Texas and Louisiana. However, the Paleozoic geologic periods were of long duration, so that time, aided by such factors as energy of the small but oft-repeated tides of the earth's solid crust, may have helped induce settling and compaction. In Tertiary strata of various regions of the world, source beds not more than a few million years in age have evidently furnished oil to associated reservoirs. Uranium data suggest that the whole Tertiary-Quaternary Era represents about 60 million years; the Cambro-Ordovician interval alone probably spans about 150 million years, with a lapse of another 150 to 200 million years for the remainder of the Paleozoic Era. Even though initiation of migration may relatively have been delayed in the Cambro-Ordovician sediments of the Appalachian region, the time spans are so great and total thicknesses of sediments are sufficient to suggest that early-stage accumulations of petroleum must have developed long before the close of Paleozoic deposition.

The thick marine clays of higher parts of the Ordovician of Pennsylvania and New York, were structurally weak and presumably yielded considerable proportions of their fluids at fairly early stages. In the subjacent parts of the Cambro-Ordovician, clays were not large in volume except in the Lower Cambrian toward southeastern Pennsylvania, and in the possible Ordovician of southeastern Pennsylvania that today is incorporated in the Wissahickon schists.

The Cambro-Ordovician limestones as they now exist in the Pennsylvania region, are strong and competent. Portions of these limestones must have originated as chalky flocculates, susceptible with increasing burial to both compaction and self-cementation with tendency to drive fluids into and in varying extent through the associated sediments. It may well be that such fairly early-stage expulsion of water is the prime cause of observed stylolites in these carbonate strata.

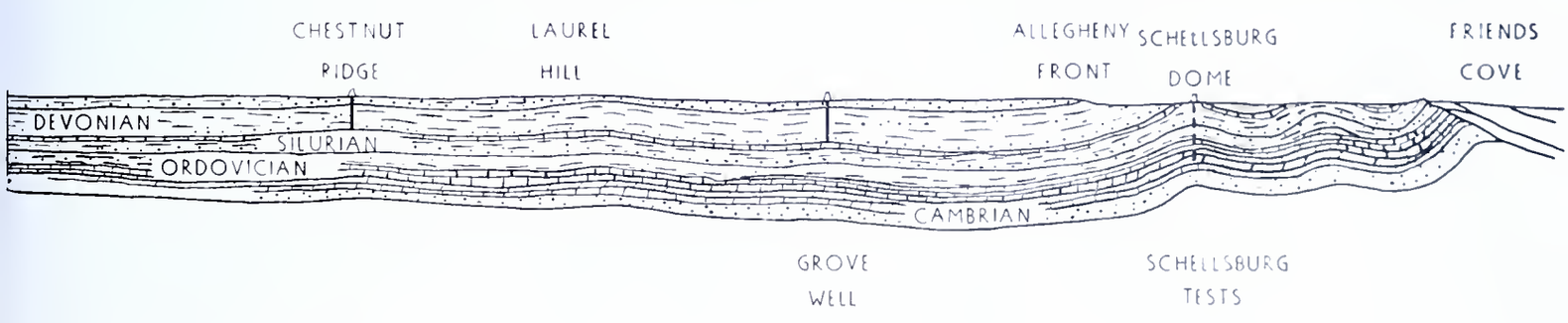
Insofar as the heavier bedded carbonate layers achieved competency at comparatively early stages, and retained well-bridged openings, expulsion of fluids would have been retarded.

If significant migration from source beds to initial reservoirs occurred, as is here envisioned, early in the post-depositional history of the Cambro-Ordovician sediments, the early-stage reservoirs were controlled by the permeability and structural relations of that time rather than of the present day. Furthermore, effects may have developed that modified possibilities of re-migration under changing conditions of later geologic periods.

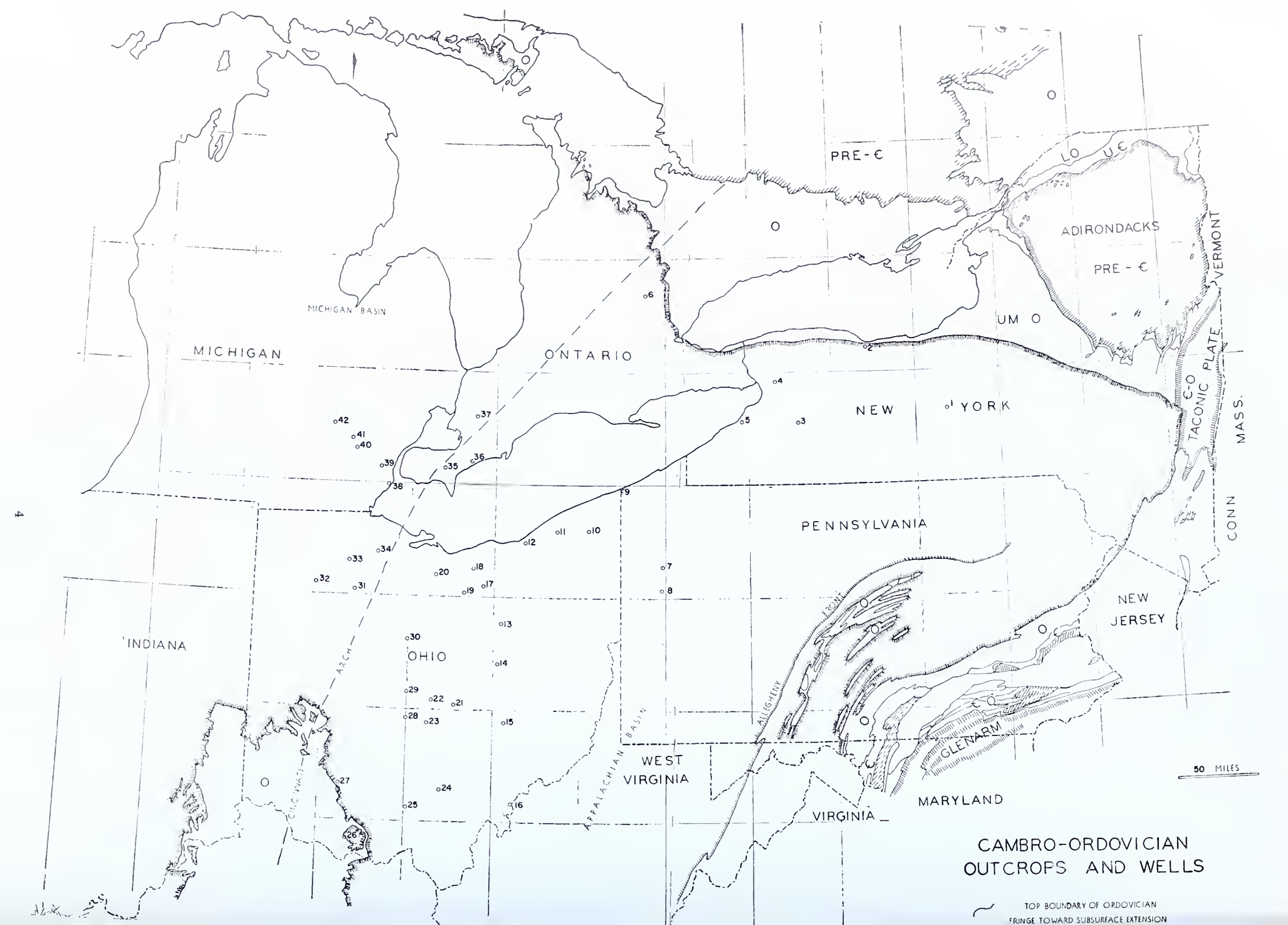
During the progress of Cambro-Ordovician and later Paleozoic sedimentation, regional dips developed in parts of the Appalachian basin, sufficient to modify migration within limits imposed by permeability patterns plus local reversals in structure.

In the Pennsylvania region, the axes of maximum thicknesses of successive stages of Paleozoic sedimentation extended generally in a northeast-southwest direction, shifting location so they crossed central to southeastern parts of the state.

Westerly thinning of the sedimentary sheets from the respective axes of greatest thickness was associated with development of an appreciable regional slope, rising northwestward. Thus the 6,000 to 7,000 feet of Ordovician sediments that overlie the Upper Cambrian Gatesburg sandy dolomites in central Pennsylvania near the Allegheny Front,



DEEP TESTS IN SOUTH CENTRAL PENNSYLVANIA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ALLEGHENY FRONT
APPALACHIAN BASIN
WEST VIRGINIA
VIRGINIA
MARYLAND
GLENARM
50 MILES
CAMBRO-ORDOVICIAN
OUTCROPS AND WELLS
TOP BOUNDARY OF ORDOVICIAN
FRINGE TOWARD SUBSURFACE EXTENSION

thin to 3,000 feet in the Hockenberry well 80 miles to the northwest. Even if the surface of sedimentation at the close of Ordovician time was as much as 500 feet lower in the Hockenberry well area than in the Allegheny Front region, the Gatesburg sediments would have risen westward with average slopes of between 30 and 40 feet per mile. By the end of Silurian time the westward rise of the Gatesburg beds should have averaged 45 to 55 feet per mile, and by the end of Devonian time may have been 80 to 100 feet per mile. Stratigraphic thicknesses used for these approximations are those of sediments as now compacted; in the stages of lesser compaction of Mid-Paleozoic time the thickness differentials may have been greater and if so the cited slopes are too gentle.

It is apparent that in Mid-Paleozoic time appreciable slopes were developed in the Cambro-Ordovician sediments of western Pennsylvania, that favored northwestward migration of oil and gas along any suitably permeable horizons, provided that water driven out in progressive compaction of the sediments moved up the slopes of the strata in its escape toward ground surface.

Countering extensive northwestward upslope movements of the oil and gas were several factors that may have retained large accumulations in areas neighboring the source sediments from which they were generated. These factors were both structural and stratigraphic.

Finn* reports that several anticlines in western Pennsylvania appear to have been weakly active during at least later phases of Paleozoic sedimentation, and evidence of similar activity is given for one of the western New York anticlines in an unpublished study by L. F. Adams and the writer. Such anticlinal activity may locally have caused reversal of the regional northwesterly rise of the Cambro-Ordovician strata, and if so may have caused some local trapping of oil and gas in any available permeable and porous horizons.

The importance of such early arching remains uncertain today because of inadequacy of information about the degree of structural activity, and about values of the reversals of dip that may have developed. Greater significance probably attaches to changing permeabilities due to variable textures of the original sediments, to leaching effects associated with surfaces of unconformity, and to differing amounts of cements deposited in the rock interstices.

There is evidence that members of a water-oil-gas system react in differing manners to variations of permeability of a medium through which they are caused to move. If such a system is driven through sandy sediments varying in texture and thus in character of the interstices, it appears that the oil and gas will tend to accumulate where the interstitial openings are coarser, whereas water may continue onward through finer openings. In-so-far as this relationship prevailed in movement of fluids in the Cambro-Ordovician sediments, early migration of oil and gas may have been significantly different from that of associated water; and conditions that drove to the ground surface much of the original water expulsed by the growing weight of overburden, may have left in subsurface reservoirs greater proportions of the oil and gas then developed.

Where and when significant quantities of oil and gas accumulated in local parts of a permeable zone, conditions were established which tended to retard cementation in comparison to neighboring areas where the same permeable horizon was charged with water alone. Such differential cementation, if it occurred, favored development of barriers to subsequent remigration of the oil and gas accumulations, whereas it simultaneously helped maintain porosity in areas occupied by oil and gas under conditions that governed the early-stage migrations.

The structural relations that favored early-stage northwestward rise of the strata across the western half of Pennsylvania, did not persist across the central part of the state. Instead, shifts at successive horizons in location of axes of maximum thicknesses of sediments, caused irregular curvatures of the earlier strata. In part, these can be approximated by studies of the accompanying isopachous maps. Any broad regional arches would have tended to localize early-stage petroleum accumulations.

Reservoir and Petroleum Possibilities In Relation to Deep Burial and To Rock Deformation

Petroleum possibilities of the Cambro-Ordovician strata of Pennsylvania have been modified by burial beneath the deep rock cover built by continued Paleozoic sedimentation, and also by temperatures and pressures developed during Late Paleozoic mountain making. In part, the effective processes acted upon storage capacities of the reservoir horizons, and altered conditions of entrapment; in part, the petroleum itself must have undergone changes in chemical and physical characteristics.

Effects of Appalachian deformation on Cambro-Ordovician strata are most pronounced in Pennsylvania in the areas neighboring Chester Valley, southeast of Lancaster in the southeastern part of the state. Here parts of the Cambrian rocks are metaquartzites, schists, and low-grade marbles, and metamorphic structures permeate Wissahickon and Peters Creek schists that plausibly represent Ordovician clays and sands. Distinct metamorphic effects persist northwards into the Bangor region of eastern Pennsylvania, where Ordovician clay sediments are quarried for roofing slate. Lower Cambrian deposits include phyllites and metaquartzites westwards into the South Mountains region of south central Pennsylvania.

The Cambro-Ordovician formations incorporated in these metamorphic terranes mostly originated as marine and brackish-water sediments, and presumably included deposits having original promise as petroleum source and reservoir horizons. The changes through which they have passed certainly dissipated any petroleum accumulations that may have developed in them during early stages of their history. The problems remain: How far to the north, northwest, and west were the metamorphic processes sufficiently active to disperse the oil and gas that may in the past have been present? What boundaries mark the limits of areas in which search for oil and gas is profitable?

The recrystallization involved in metamorphism of the Cambro-Ordovician strata of the Lancaster region, affected relatively stable mineral materials. In contrast, David White in propounding the "carbon ratio" hypothesis, many years ago drew analogy between petroleum occurrences and the pattern of change in constitution of coal, which more than the inorganic minerals is likely to have reacted to processes apt to cause modification of petroleum. White recognized that oil fields discovered in Upper Devonian and Carboniferous strata of Pennsylvania mostly lie to the west of the 60 per cent "fixed carbon" line of the Carboniferous coals; whereas commercial gas fields of the same general group of strata extend farther to the southeast but are on the whole limited by the 65 per cent "fixed carbon" line. Upper Devonian and Carboniferous oil and gas fields in Pennsylvania have not been much extended by subsequent drilling; as in White's day, they still are restricted to the northwestern two-thirds of the area northwest of the Allegheny Front. (Compare Figure 2.) Considered as a whole and without relation to indi-

*Finn, F. H., personal communication, 1948.

Figure 2—Index map, showing Cambro-Ordovician outcrop belts along the rim of the northern part of the present-day Appalachian structural basin, and general location of the Cincinnati arch which bounds the basin on the west. A different version of the Findlay or Ohio section of the arch is illustrated in Figure 12. The crop of the top of Ordovician sediments along margins of the Appalachian basin and elsewhere, is shown by a prominent, fringed line; the fringe is directed toward the subsurface extension of the Ordovician strata.

Wells especially important for subsurface data are numbered as follows: in NEW YORK: 1, Reserve Oil Company's J. C. Mahaney No. 1 well; 2, Old Rochester well; 3, K. R. Wilson's Arcade No. 1 well; 4, Depew No. 2; 5, Bemus Pierce well; PENNSYLVANIA: 7, United Natural Gas Company's Maude Davidson No. 1 well; 8, Manufacturers Light and Heat Company's Jessie G. Hockenberry No. 1 well; 9, Ohio Oil Company's Jay Childs No. 1 well; OHIO: 10, Ohio Fuel Gas Company's George E. Chester No. 1 well; 11, East Ohio Gas Company's Crile No. 1 well; 12, Newburg and Cleavland No. 4 well; 13, Ohio Oil Company's J. H. Armstrong No. 8 well; 14, Ohio Oil Company's Chaney-Meyer, Unit 2, No. 1 well; 15, Industrial Gas Corporation's Sidney Whitmore No. 1 well; 16, Sinclair Prairie Oil Company's George Longsworth No. 1 well; 17, McCrea Oil and Gas Company et al. Billman No. 2 well; 18, Hanley and Bird's Grant W. Pitts No. 1 well; 19, Ohio Oil Company's S. V. Krause No. 1 well; 20, C. W. White's Peter and Blanch Arting No. 1 well; 21, W. W. and A. T. Wherle No. 8 well; 22, S. D. and W. B. McClay's Bertha Rowe No. 1 well; 23, Community Stemen No. 1 well; 24, Ohio Fuel Gas Company's George E. Chester No. 1 well; 25, Waverly well; 26, H. J. Popham No. 1 well; 27, New Vienna well; 28, Columbus well; 29, Chester L. Wise et al. Herman E. Vance No. 1 well; 30, Ohio Fuel Supply's Ulsh No. 1 well; 31, Findlay well; 32, Ohio Oil Company's Louis Barlage No. 1 well; 33, Schwyn's Brailey No. 8 well; 34, Ohio Oil Company's Bruns No. 1 well; ONTARIO: 6, Rockwood Oil and Gas Company's well; 35, Union Gas Company's Imperial Oil No. 3 well; 36, Dominion Gas Company's Shanks No. 6 well; 37, Union Gas Company's No. 8 well; MICHIGAN: 38, Sturman's Chapmon's No. 1 well; 39, Colvin's Theisen No. 1 well; 40, Colvin's Meinzinger No. 1 well; 41, Colvin's Voss No. 1 well; 42, Duck Lake Oil Company's McPherson No. 1 well.

vidual geologic horizons, these fields tend to form an oil belt and a gas belt strikingly parallel to each other, to the isocarb lines of the Pennsylvanian coals, and to the Allegheny Front whose trend expresses the strike of Appalachian deformation.

On the basis of these geographic relationships, White attributed the southeasterly changes in both petroleum and coal to increased stresses of Appalachian mountain making. The conditions suggest, according to this view, that there is a parallel between increased driving off of volatile constituents of the coals, and breakdown of oil into heavy hydrocarbons and gaseous fractions, generally with the natural gas dispersed from the rocks in those areas where the coals measure more than 65 per cent in fixed carbon.

The chemistries of both the coals and petroleum of the Pennsylvania region change in a general way with depth as well as horizontally. Within the Pennsylvanian sediments, there is decrease in volatile constituents in successively deeper coal beds of comparable type. In the petroleum accumulations of these and deeper strata, both oil and gas occur in commercial quantities in Upper Devonian horizons of northwestern Pennsylvania and southwestern New York, whereas in geologically deeper Lower Devonian, Silurian, and Middle Ordovician productive layers, the known pools furnish gas but not oil. Oil does occur in more westerly extensions of these deeper rocks, in Ohio and Ontario, as might be expected from the carbon-ratio suppositions.

If the changes at successive geologic depths of the coal and petroleum of the region represented a non-complex parallelism with the southeastward geographic changes in the shallower Upper Devonian and Carboniferous occurrences, related to the belts of Appalachian mountain-making in the fashion postulated by White, it would be expected that the boundary between gas-bearing and non-gas-bearing areas would shift northwestwards at successively deeper horizons. However, within the Upper Devonian sequence itself the limits of occurrence tend to shift southeastwards rather than northwestwards in the deeper strata. In the much deeper, Lower Devonian Oriskany sandstone, several important gas fields have been brought in southeast of the 65 per cent fixed-carbon line that approximates the limit of discovered Upper Devonian gas production. (Compare Finn, 1949.) Even with this extension, Oriskany production in Pennsylvania is bounded by the 70 per cent fixed carbon line of the Pennsylvania coals; but this seeming limitation may be illusive since exploration southeast of the line has been retarded by increasing depth of the formation.

Southeastward shift of the margin of gas production in the successively deeper Upper Devonian sands would not be expected from the carbon ratio hypothesis; localization of these accumulations is now known to be controlled in large degree by facies of sedimentation. (Sherrill, Dickey, Matteson, 1941.) The southeastward shift of discovered occurrences in the still deeper Oriskany sandstone presents a further anomaly. Added encouragement for questioning the carbon-ratio hypothesis and for favoring some southeastward extension of exploration comes from discovery, southeast of the Allegheny Front in Virginia, of the Rose Hill oil field in the Trenton limestone as well as of the Bergton gas field in the Oriskany sandstone.

With specific reference to the Cambro-Ordovician strata of the Pennsylvania region, it may be that the considerable weight of overburden at the time of Appalachian deformation helped to close off openings through which escape might otherwise have been more active. Where thick and competent dolomites and limestones served as reservoirs, reactions to both mechanical deformation and chemical modification may have differed significantly from results that might have developed if the reservoirs had consisted of quartzose sands comparable to the Oriskany, or of somewhat more graywackyish sands such as those of the Upper Devonian.

In summary, both depth of burial and facies relationships may have induced, in the Cambro-Ordovician strata, patterns of petroleum occurrence somewhat different from those so far discovered in geologically higher strata. Exploration in areas neighboring the Allegheny Front may be justifiable on a high risk, venture basis, and will be necessary for further analysis of possibilities. Even though the carbon ratio hypothesis as developed by White may need modification in the light of future discoveries, the basic concept that southeastward extent of petroleum occurrence in Pennsylvania must at some place be limited by effects associated with Appalachian deformation, can not be wholly disregarded. Since only gas is known in Lower Devonian and geologically deeper horizons in Pennsylvania and New York, it does not appear likely that future discoveries in the Cambro-Ordovician of these states will furnish oil in significant amounts.

Regional Trends of the Cambrian, Ordovician Sediments, Northern Appalachian Basin, and Relation to Oil and Gas Possibilities

General Features of the Cambro-Ordovician Sediments

Where exposed in central and south-central Pennsylvania, Cambro-Ordovician sediments reach a maximum thickness of about 15,000 feet. (See Figures 3, 1.)

Of this thickness, the basal 3,000 to 4,000 feet consist of quartzitic sandstones, and clay shales locally metamorphosed to phyllites; the median 8,000 to 10,000 feet are composed mostly of limestones and dolomites with sandstone interlayers in the middle part; and the upper 2,500 to 3,000 feet include shales, graywackyish sandstones, some conglomerates, and reddish shales and sandstones.

The Ordovician sediments thin gradually as they are traced from outcrop belts in central Pennsylvania into their subsurface regions in western Pennsylvania and western New York.

Information is more scanty about changes taking place in the Cambrian sediments as they extend into the same subsurface areas; but there are reasons to believe that the Cambrian strata undergo more marked reductions in thickness, chiefly because of uncomformable disappearance of the lower beds. (See Figure 3.)

Subdivision of this complex of sediments into Lower Cambrian, Middle and Upper Cambrian, Lower Ordovician, Middle Ordovician Chazy, Middle Ordovician Black River and Trenton, Middle and Upper Ordovician shales, and Upper Ordovician sandstone and red bed deposits, is indicated in Figure 3. The regional geology of each of the subdivisions is hereinafter discussed, and is illustrated by isopachous-isolithic maps, as a basis for consideration of oil and gas possibilities.

The manner in which the individual isolithic-isopachous maps have been built up, is well exemplified by accompanying diagrams for the Lower Ordovician Beekmantown deposits. Stratigraphic studies of the type illustrated in Figure 10, using locally established sections correlated by fossil faunas and by lithologic continuity or interfingering, establish changing characters of the sediments in present-day exposures, and reveal basic trends in thicknesses and facies used in construction of the preliminary map of Figure 8. In Figure 9, these same basic trends have been projected farther through subsurface areas, using checks and balances available from the few deep wells that have penetrated Beekmantown strata, or that reached the Beekmantown horizon and found rocks of this age-group absent by unconformity.

The distribution, thickness variations, and rock characters illustrated in comparatively objective fashion in maps of the type shown in Figures 8 and 9, reflect the geography of the age, and geographic factors of sedimentation are constantly considered in their construction. Such maps represent solutions of problems of ancient geographies; changes from sand deposits to clay materials and to limestones and dolomites, as well as from marine to fresh water sediments, should be in accord with the geographic probabilities that are consonant with the known stratigraphic facts.

Reviewing the entire accompanying suite of isopachous and isolithic maps, several major structural features of the ancient platform become apparent.

Figure 3.—General stratigraphy of Ordovician and Cambrian sediments from southcentral Pennsylvania to the Hockenberry well in western Pennsylvania and the Wilson or Arcade and Rochester wells in western New York. Sandstones and sandstone interlayers are indicated by stippling, conglomerates by a pattern of small circles, shales by dashed lines paralleling the general bedding. Limestones and dolomites are left blank, without a pattern, but are indicated by LS and DOL following the name of the respective formations.

These profoundly affected the course of Cambro-Ordovician sedimentation.

Through most of Cambro-Ordovician time, a belt of subsidence crossed Pennsylvania and extended northeastwards toward Vermont. For long periods, marine waters flooded extensive parts of this broadly trough-like area, and at times spread northwestwards in a shallow sheet that inundated the Cincinnati arch of lesser downwarp and merged with seas of Michigan and Indiana. During other intervals, the Cincinnati arch-belt was gently emergent, exposing its sedimentary cover to shallow weathering and some erosion.

In New York, the Adirondack area tended to remain above water, and varied geographically from an eastwardly jutting peninsula to a temporarily isolated island.

In Upper Cambrian time, land surfaces on the north furnished sands that spread widely in the shallow seas. By the middle of the Ordovician, easterly lands began to rise and suffered increasingly vigorous erosion, so that geographic outlines and conditions of sedimentation were greatly altered.

The geographic changes that marked successive stages of the Cambro-Ordovician history of the Pennsylvania region, gave rise to the differing sedimentary patterns described and illustrated on succeeding pages.

Lower Cambrian Sediments

In Lower Cambrian time, a trough-like depression subsided across southeastern Pennsylvania, was flooded by shallow seas, and received sands and clays vigorously eroded from neighboring, rising land surfaces. Before the close of the Lower Cambrian interval, however, the lands had been reduced to low altitudes, the waters of the trough became clearer, and carbonate sediments became dominant.

The course of the trough, and the history of its subsidence as well as of elevation and erosion of adjacent land areas, are recorded in the accumulated sediments that now crop out as lithified rock layers, and that are reconstructed in Figure 4 to show approximately the original extent and thicknesses.

In the South Mountains area of southcentral Pennsylvania, thicknesses of 4,000 to possibly 5,000 feet are reported for Lower Cambrian strata. The lower 3,000 to 4,000 feet consist of sands and clays and some gravels; upper beds are composed of limestones and dolomites with subordinate clays and sands. The limestone and dolomite formations contain distinctive **Olenellus** trilobite fossils, and were deposited in marine waters. In underlying beds, fossils are very rare except for tubes of worms that may have inhabited muddy and sandy tidal flats. Sorting and separation of much of the

substantially equivalent sands and muds, and good cleansing of thick deposits of quartz sands, suggest the work of surf and currents of extensive, shallow seas, rather than deposition on flood plains or in estuaries.

The Lower Cambrian sediments thin gradually northeastwards along the axis of the ancient trough, more rapidly in the direction of the margins. In eastern Pennsylvania, they include basal conglomeratic quartzites and overlying, partially recrystallized limestones, subequal in thickness. In the southern part of the Hudson River Valley in New York, the basal quartz sandrock is thinner, the overlying limestones deformed and their thickness uncertain. Farther north in the Hudson River Valley, there are about a thousand feet of sandy Lower Cambrian shales, believed to have been deposited farther to the east and moved to their present location by Taconic overthrusting. In Vermont, the Lower Cambrian is composed of dolomites, sandy dolomites, and some quartzitic sandstones and slates.

Northwestward from their axis of thick development, the Lower Cambrian sediments thin out and disappear. They are missing where their horizon reaches ground surface along the margins of the Adirondack Mountains, as well as in Ontario north of Lake Ontario. (See Figure 4.) They are absent at the base of Upper Cambrian formations in wells in southwestern Ohio, northern Ohio, and in Michigan. They reportedly are absent in the deep well at Rochester, New York, in the Depew No. 2 well and George Button wells nearer Lake Erie, and in several deep wells drilled to the Pre-Cambrian in northern Ohio and southwestern Ontario.

Projection of the Lower Cambrian sediments into their subsurface extensions, and prediction of changes in thickness and rock character, are hindered by incomplete knowledge of textural patterns of the detrital sediments in areas of exposure, as well as by the great distances from outcrop belts to the deep wells that have reached their horizon but found them missing. The problems along the outcrop belts largely result because of difficulties in establishing close age correlations and directions of interfingering of changing facies of sediments of closely equivalent ages.

In Vermont, it is clear that during Lower Cambrian time much sand was derived from the Adirondack region on the west. Some clays and other sands concurrently were coming from low-lying lands east of the trough of sedimentation.

In the Hudson River Valley, the sandy shales of the Taconic overthrust slices probably represent clays and sands originally derived from easterly, eroding Lower Cambrian land surfaces. The basal quartz sands of the Lower Cambrian farther south in the valley could, however, have been received from the west.

In southern Pennsylvania, the thickest and coarsest Lower Cambrian gravel-bearing rocks occur in the middle part of York County and adjacent parts of Lancaster County, east of the South Mountains where pebbles are fewer in number. Within the South Mountains area itself, some clay rocks change northeastwards and eastwards into sand. These changes as now known suggest derivation of the detritals from easterly or southeasterly land surfaces. The textural pattern is, however, obscured by uncertainties in detailed correlations. A cogent argument might be developed that much detrital material could have been swept in from the north, with a gravel-rich lobe extending southwards into the present York County area.

If the Lower Cambrian gravels, sands, and clays of the southern Pennsylvania region actually were derived from the southeast, there should be decrease in coarseness as well as thickness of detritals as the sediments extend underground to the north, northwest, and west of the present-day belts of outcrop. There could be some increase in proportion of the carbonate rocks. If the detritals were chiefly derived from the north or northwest, then the detrital changes in the subsurface regions would be markedly different, with northward coarsening of textures and probably more rapid northward rate of disappearance. Further information will be required before this problem can be definitely solved, although probabilities favor derivation from the southeast.

Whatever the details, it is reasonably certain that the Lower Cambrian sediments disappear northward, northwestward, and westward from central Pennsylvania before reaching the south shore of Lake Ontario, and the northern and central parts of Ohio. Location of the line of zero thickness shown crossing northern and western Pennsylvania in Figure 4 is however problematical; it could belong 50 or even as much as 100 miles farther to the northwest, though such major shift to the south is less likely.

Exposed parts of the Lower Cambrian sediments as they exist today are affected by metamorphism. In the Chester Valley-Mine Ridge region of southeastern Pennsylvania, the Harpers formation has been transformed from original silty clay into an albite-chlorite schist; the more clayey or graywackyish parts of the sand sediments also are schistose, and the limestones and dolomites are partially recrystallized and turned at some places into low-grade marbles. Regional metamorphism persists with some decrease in intensity, westwards to the South Mountains of southcentral Pennsylvania.

Oil and Gas Possibilities of The Lower Cambrian Sediments

Oil and gas possibilities of subsurface parts of the Lower Cambrian sediments of Pennsylvania and New York are affected by both favorable and unfavorable factors. Their problems are further complicated by uncertainty about trends in change from sands to clays and to carbonates. Despite the difficulties, several discernible relationships deserve attention as consideration is given to these deepest Paleozoic sediments.

In the first place, the carbonates and some of the highest detritals of the Lower Cambrian of outcrop belts in Pennsylvania are definitely marine, and much of the subjacent sands and clays probably originated in marine or brackish waters. Especially if the detrital sediments were chiefly derived from the southeast, it is likely that the northerly and westerly subsurface extensions are marine or estuarine, deposited in a shallow trough that may at times have reached widths of 100 to 200 miles. The general nature of the sediments suggests that they included possible source and reservoir deposits.

Much of the transformation into petroleum of any suitable organic matter in the Lower Cambrian sediments, is likely to have occurred by Middle Paleozoic time. By that stage, structures were developing that should have affected migration. Shifting position of the axis of greatest subsidence and sedimentation to and fro between southeastern and central Pennsylvania, warped the Lower Cambrian and may have produced structures favorable for localization of oil or gas accumulations. Northwest of the Allegheny Front, on the other hand, the Paleozoic sediments thinned, and an appreciable northwesterly rise was being developed favorable to updip petroleum migration in any permeable horizons. Updip migrations so far as they occurred were impeded chiefly by discontinuities of permeability, that may be especially marked toward the northwesterly pinchout margin of the Lower Cambrian sediments. (See Figure 4.) Whether there were in this belt any early-stage arches sufficient to interfere with the northwesterly migration is unknown. Configuration of the sub-Cambrian surface, and its effect on structures in the Cambrian strata, also cannot be judged.

Even if the bulk of the Lower Cambrian detritals was derived from the southeast, it is likely that some sands, favorable as potential reservoirs, were washed into the trough from the northwest.

In their belts of outcrop in southeastern Pennsylvania, the Lower Cambrian

sediments are affected by strong regional metamorphism, probably Late Paleozoic in age for the most part. The metamorphic effects gradually diminish toward the west and north. As far west as the South Mountains near Gettysburg, metamorphism is so marked that any oil and gas accumulations must have been dispersed. Metamorphic effects expectedly will persist farther to the north and west in these deep strata than in younger and shallower parts of the Paleozoic succession, and likelihood of petroleum in the Lower Cambrian does not appear good, in the southeasterly half at least, of the folded Appalachians.

At and northwest of the Allegheny Front in Pennsylvania, the Lower Cambrian sediments lie at great depth, the order of magnitude about four miles. Farther northwest the depth gradually diminishes, but even near the margin of the strata as drawn in Figure 4, it will be about two to two and a half miles. Hence, although this marginal region appears to be the most favorable belt for any Lower Cambrian petroleum occurrences, the depth will discourage exploration.

Middle and Upper Cambrian Sediments

The Middle Cambrian seas of the Pennsylvania region were comparable to those of the Lower Cambrian in size and geographic distribution. In Upper Cambrian time, however, the areas of subsidence and submergence were greatly broadened, so that sedimentation spread far to the northwest of its earlier limits, extending across most of Pennsylvania, New York, Ohio, and southwestern Ontario, to and beyond Michigan.

Even in the most widespread stages of Upper Cambrian flooding, a small dome was emergent in the western Adirondacks, and deposition seems to have been lacking along part of the Cincinnati or Algonquin line northwest of present Lake Ontario. Absence of Upper Cambrian sediments in some of these areas may involve post-Cambrian erosion, and post-depositional erosion may also have modified Upper Cambrian formations in southeastern Pennsylvania. (See Figures 5, 6.)

The isopachous lines of Figure 5 show approximate thickness distributions for the combined Middle and Upper Cambrian sediments of the region. Middle Cambrian deposits may well be confined to the area south of the 2,000-foot line that crosses northwestern Pennsylvania. Where thicknesses of the combined Middle and Upper Cambrian sediments range from 3,000 to 4,000 feet, the Middle Cambrian as understood varies from about 500 to 1,500 feet.

The thickness variations of the Middle and Upper Cambrian reflect the geography of major tectonic elements of the ancient platform of sedimentation. The Cincinnati-Algonquin axis is an axis of thinning of the sediments, and probably of shoaling and occasional emergence. A dome persisted in the western Adirondacks. The axis of maximum thickness crossing southeastern Pennsylvania presumably reflects the average axis of maximum subsidence; it may in this instance approximate the average axis of deepest water, since it was a region of slowly deposited carbonates and not of rapidly deposited detritals. The axis of deepest water probably shifted considerably during the long-continued period of Middle and Upper Cambrian sedimentation.

The Middle and Upper Cambrian sediments represented in Figure 5 predominantly were deposited by marine to perhaps somewhat brackish waters. The reddish arkosic Jacobsville sandstone at the base of the Upper Cambrian of Michigan may have been deposited by fresh waters; its classification as Upper Cambrian also remains questionable. Reddish arkosic sandstones of the lower Potsdam of the northern and northeastern flanks of the Adirondacks may also be largely non-marine.

Middle Cambrian sediments where known in Pennsylvania consist mostly of carbonates. Lands neighboring the trough-region were low and furnished little detritus. Some clay did mingle with carbonates of the Elbrook limestone of southeastern Pennsylvania, and of the lower half of the Pleasant Hill limestone of the central part of the state. (See Figure 6.)

The broadening subsidence of Upper Cambrian time was accompanied by moderate upwarp of northerly lands, so that quartzose sands transported onto the platform of deposition were moved southeastward, progressively decreasing in proportion in the sediment. Sands form a third to a half of the Upper Cambrian of Michigan, southwestern Ontario, and northern Ohio; about a quarter of the Upper Cambrian of the Arcade well of western New York; they

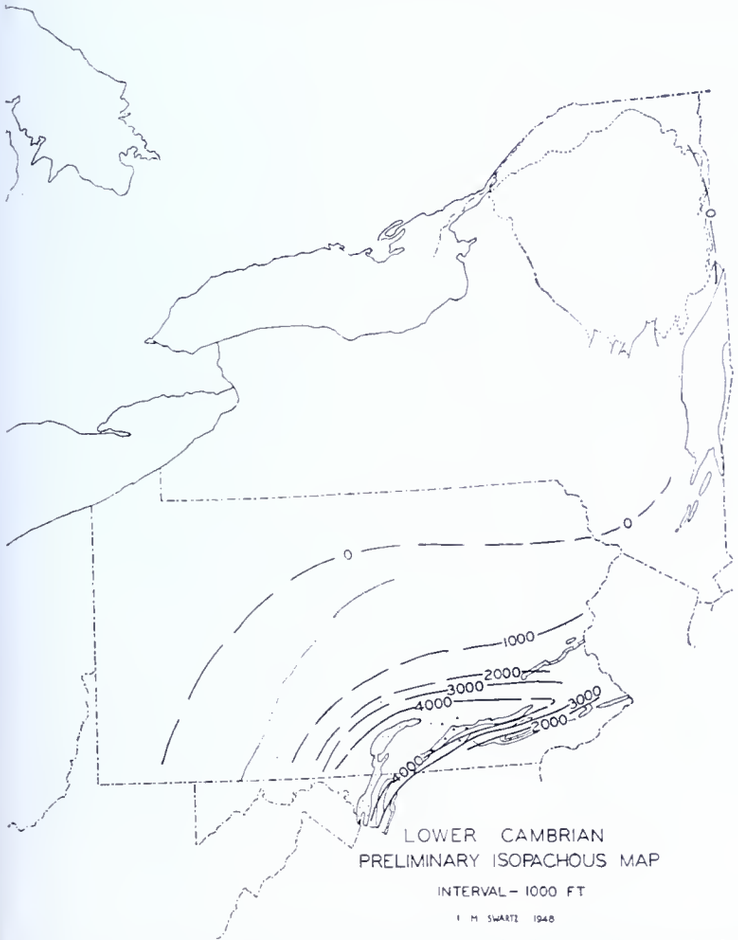

Figure 4.—Preliminary isopachous map of Lower Cambrian sediments. Dashed lines in the Adirondack area and in Ontario show outcrop belts along which Lower Cambrian strata are missing by unconformity.

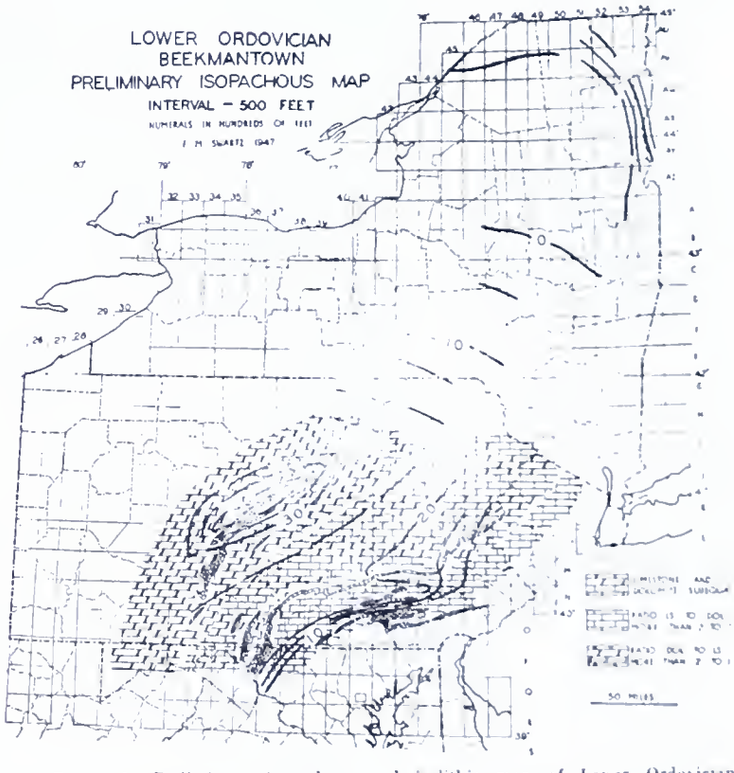

Figure 8.—Preliminary isopachous and isolithic map of Lower Ordovician Beekmantown sediments as based on sections along outcrop belts in the Pennsylvania-New York region. The map is figured here to illustrate a basic step in development of the more complete map in Figure 9.

are reduced to less than a tenth of the mass in the Upper Cambrian strata of central Pennsylvania, and virtually are lacking in the Upper Cambrian of southeastern Pennsylvania. The Upper Cambrian sands thickly developed along the northeastern flank of the Adirondacks of New York, seem in large degree to have developed independently of the sands farther to the west and southwest.

The greater part of the Upper Cambrian detritals of the general region are quartz sands with surprisingly small proportions of other materials. In Michigan, minor shales are present, and some clay is represented in subordinate shaly sandstones and shaly dolomites. Some portions of both the sandstones and dolomites of Michigan are glauconitic. Along the flanks of the Adirondacks, initial sands largely are arkosic, higher sands clean-washed and quartzose.

In the Michigan region, some of the sands in the lower part of the Upper Cambrian probably were derived by relatively local reworking of weathered and perhaps wind-sorted detritus of the platform of sedimentation. Some sands of higher parts of the Upper Cambrian were formed from older Upper Cambrian layers, exposed by shifts in margins of the seas. Such reworking on the platform of sedimentation may have helped to move sands southeastwards toward central Pennsylvania. Complication in sedimentation of sands in the Upper Cambrian of central Pennsylvania as compared to Michigan, southwestern Ontario, and northern Ohio, is evidenced by the fact that in central Pennsylvania sands are more common in the upper half of the Upper Cambrian, whereas in the more northwesterly areas they dominate the lower but not the upper portion. The sands of the Upper Cambrian of central Pennsylvania were brought in recurrently, so that they are interbedded with thicker sequences of non-sandy dolomites. In the Hollidaysburg quadrangle region (Butts, 1945), two thin sandstone tongues are represented in the Warrior limestone; sandstone interlayers are much more numerous in the Gatesburg formation. (See Figure 6.)

The lithologic patterns used in Figure 5 portray characters of the Upper Cambrian sediments. It is a striking feature of the region that the dominant Upper Cambrian carbonates are dolomites. Limestones become prominent along a belt crossing southeastern Pennsylvania, and extend in decreasing proportions into central Pennsylvania. (See both Figures 5 and 6.) In the writer's opinion, dolomitization was for the most part completed while the carbonates were fresh on the sea floor, and distribution of the dolomites and limestones reflect features of the ancient geography of sedimentation. It is less clear whether the dolomite-limestone pattern was governed by depth, salinity, temperature, or current systems of the ancient sea waters. The dolomite-limestone patterns of the Upper Cambrian, Lower Ordovician Beekmantown, and Middle Ordovician Black River-Trenton sediments all involve increase in dolomites toward the west, of limestones toward the east or southeast. In the Black River-Trenton rocks, dolomitization appears to be related to shoaling of the water. Shoaling may however be only an indirect factor,

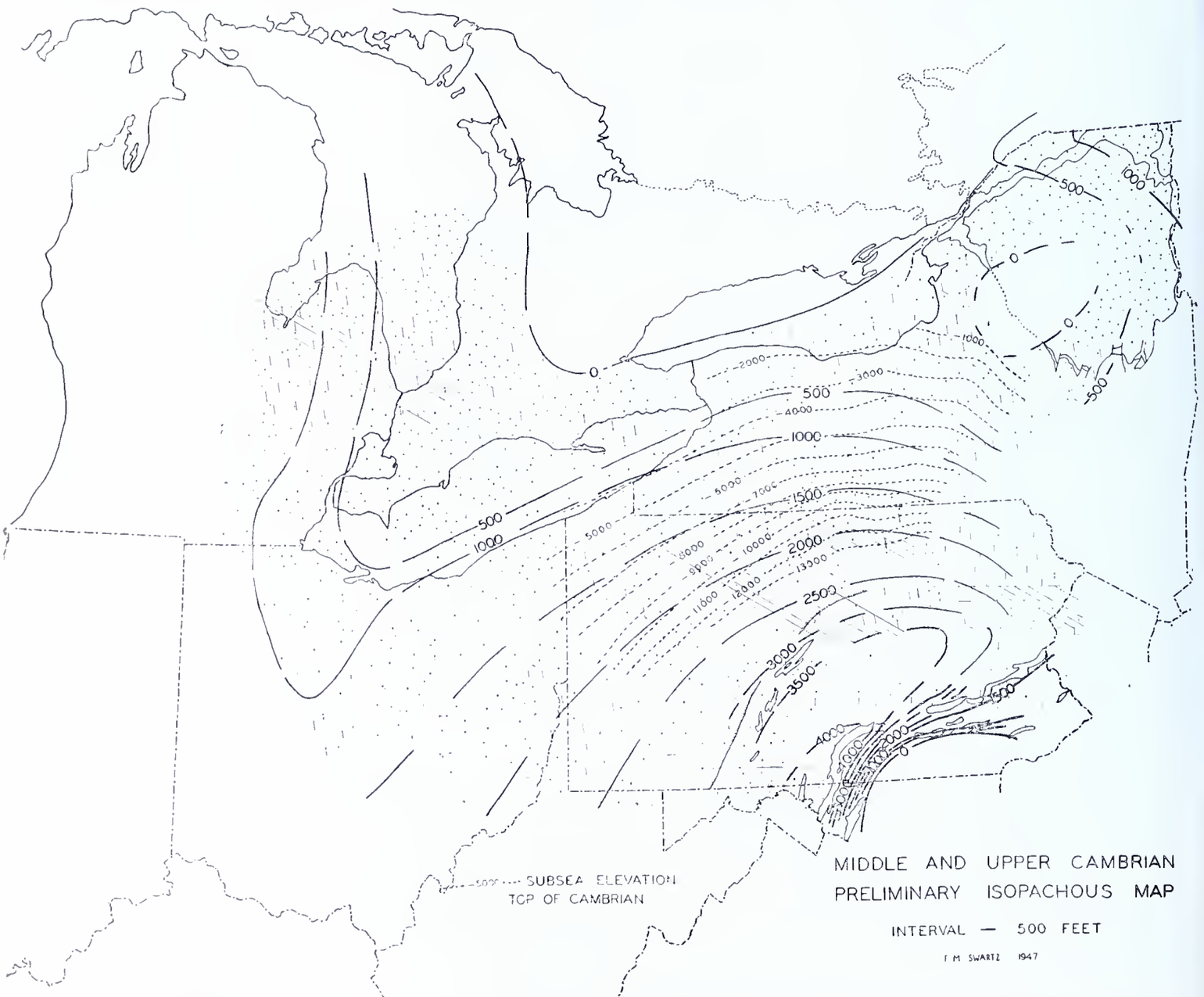

Figure 5.—Preliminary isopachous and isolithic map of Middle and Upper Cambrian sediments. Stippling indicates sandstones, oblique brick-type pattern represents dolomites, horizontal brick-type pattern signifies limestones. Outcrop areas are outlined in central and southeastern Pennsylvania and northeastern New York; dashed lines in New York and Ontario show outcrop belts where both Middle and Upper Cambrian beds disappear by unconformity. In subsurface areas in northwestern Pennsylvania and southwestern New York, subsea elevations at the summit of the Upper Cambrian are shown by dashed-line contours.

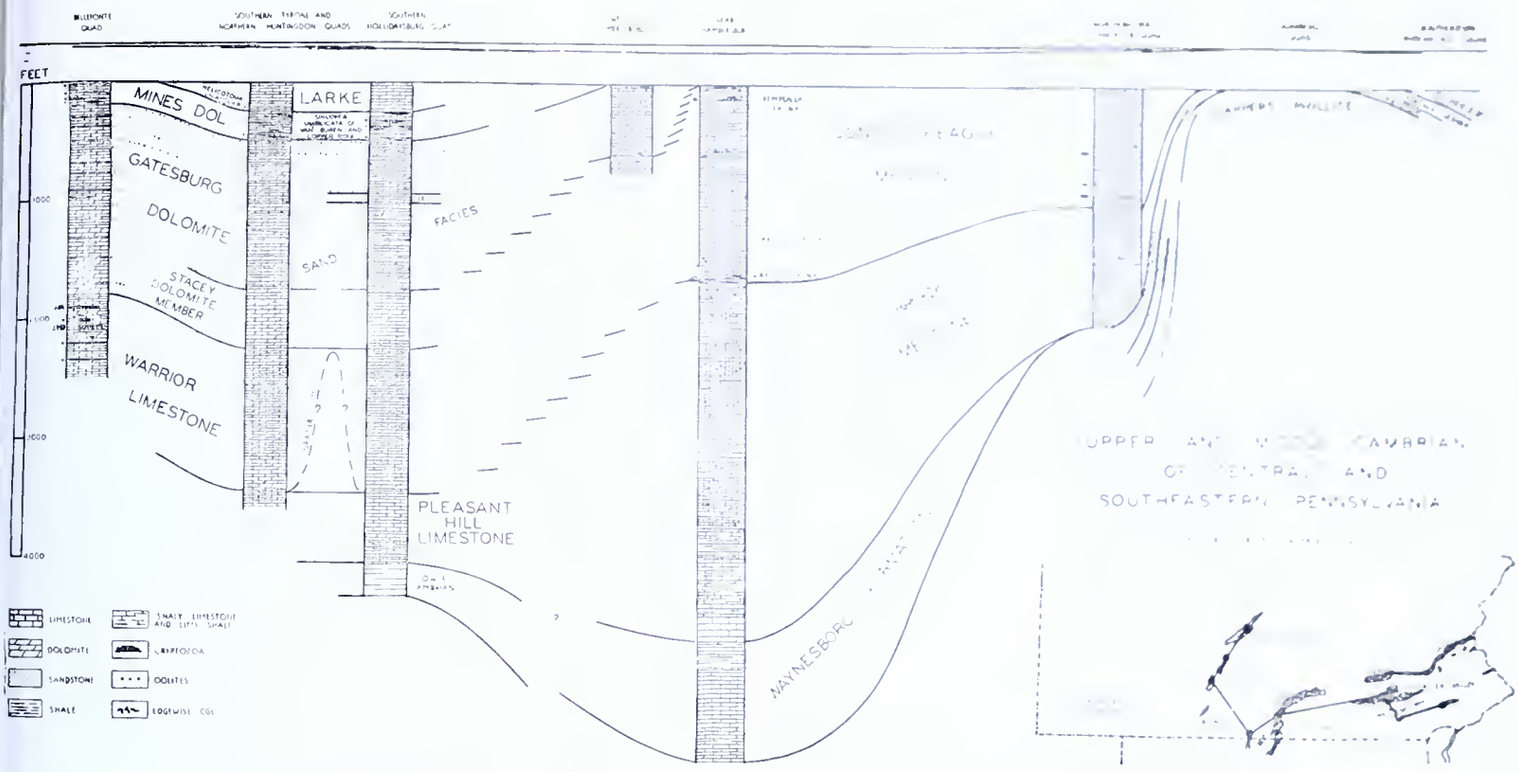

Figure 6.—Stratigraphy of Middle and Upper Cambrian sediments from central to southeastern Pennsylvania. The Waynesboro formation may be wholly Lower Cambrian. The Pleasant Hill limestone and equivalent parts of the Elbrook are Middle Cambrian. Higher formations are Upper Cambrian, except that the Larke dolomite is Lower Ordovician and the Mines has been so classed in a few publications.

associated with temperature, evaporation, salinity, and current distributions.

Oil and Gas Possibilities of the Middle and Upper Cambrian Sediments

The sandy dolomites of the Upper Cambrian of subsurface areas in western and northern Pennsylvania and south-central and western New York, afford favorable prospects for reservoir-type porosities. The regional dip of these deep strata reduces possibilities of structural closure, and thus make reservoir trapping increasingly dependent upon permeability pinch-outs. Source-bed possibilities are difficult to judge, but it is at least probable that the Upper Cambrian strata accumulated under varyingly marine to brackish water conditions, and that subjacent marine strata thicken toward the south.

Fluids have been encountered in the Upper Cambrian sandstones and dolomites in several deep wells in western Pennsylvania and western New York, giving assurance of appreciable porosity. In the J. Childs No. 1 well in western Pennsylvania, there was a slight showing of gas and oil and a little salt water at 5,185 to 5,188 feet, and more salt water at 5,188 to 5,191 feet that rose 3,000 feet in the hole. In the Hockenberry well there was a showing of gas in Upper Cambrian dolomite at 9,746 to 9,771 feet, a little salt water at 10,092 feet. In the Wilson well at Arcade, New York, salt water entered the well from Upper Cambrian sandstone at 6,375 to 6,395 feet, and at 7,040 feet there was more salt water that rose 5,500 feet. These fluids suggest that the Upper Cambrian sandstones and dolomites have definite possibilities as potential oil or gas reservoir beds.

Due to the northwesterly convergence of the Paleozoic strata, average regional rise of bedding in western and northern Pennsylvania and western New York is greater in deeper than in shallower beds, and will tend in the Upper Cambrian to reduce structural closures present in higher strata. This effect may be counterbalanced if anticlinal structures increase in amplitude with depth due to Paleozoic arching, or to forcible uplift from the deep basement.

The present average regional dips in western and northern Pennsylvania and western New York, have been accentuated by Late Paleozoic and perhaps some post-Paleozoic tilting. Regional southeasterly dip or northwesterly rise must have been appreciably developed in the Upper Cambrian strata during Paleozoic time, and may have been sufficient to allow extensive early-stage updip migrations of oil and gas, provided that water-drive was active in this direction. Permeability wedge-outs associated with lensing out of sand layers or with margins of leach-zones, may have served as the chief barriers to updip loss of petroleum during the Paleozoic history of the sediments, and doubtlessly have had important effects on any present-day reservoir locations. Significance of early-stage arching, and possible relation to dip reversals and local porosity changes, remains uncertain.

Parts of the Upper Cambrian sediments are believed to have been emergent in Early Ordovician and in Chazyan time. (See Figure 7.) Since the Beekmantown region of sedimentation is shown in maximum extent in Figure 7, possibilities of emergence and leaching of the Upper Cambrian sediments extends into the marginal Beekmantown areas. Such leached zones if developed may have given rise to residual sands porous through extensive belts.

Sandy, originally porous Upper Cambrian strata occur not only in northern and western Pennsylvania, but also extend into the folded Appalachians southeast of the Allegheny Front. Possibilities of both early-stage and late-stage structural trapping are improved in the folded area. There are a number of important anticlinal belts in which Upper Cambrian strata occur under reasonably good protective cover, without being at depths excessive for testing. At the same time, likelihood is increased of dissipation associated with Appalachian deformation.

Northwest of the Allegheny Front, the Upper Cambrian extends for some miles at depths exceeding 15,000 feet. Farther to the north and northwest, the strata gradually rise to shallower levels, their approximate elevations being shown in Figure 5 by dashed-line structural contours. Exploration will be discouraged in the deeper areas because of high cost of test wells.

Lower Ordovician Beekmantown Sediments

The tectonic elements evident in the Upper Cambrian geography of the Pennsylvania-New York-Ohio-Ontario-Michigan region, persisted in modified form into Lower Ordovician Beekmantown time, but with changes important both for sedimentation and oil and gas possibilities.

The Cincinnati-Algonquin arch became broadly though gently emergent, exposing Upper Cambrian sediments over wide areas, so that depending on altitude of land they were subject in some degree to weathering and erosion. (See Figures 7, 9.) The Adirondack dome

formed a broad, eastwardly projecting peninsula. The axis of maximum thickness of sediment and perhaps roughly of greatest subsidence crossed central Pennsylvania, and was parallel to but northwest of its average location during Middle and Upper Cambrian deposition.

The sediments deposited in this geographic setting are, so far as known, all marine. They reach a maximum thickness of about 4,000 feet in central Pennsylvania, and thin elsewhere along the northeast-southwest axis of greatest thickness, as well as to the northwest and southeast toward the margins of the trough. The trough extended northeastward across southeastern New York into Vermont, the connecting area not well known. In the Albany region of eastern New York, there are Beekmantown Deepkill shales, believed to have been thrust with associated rocks of the Taconic slices westwards from their presumed more easterly locus of sedimentation.

Beekmantown sediments are believed to be absent across southwestern Ontario and across much of Ohio, reappearing again in western Ohio. The belt of emergence represents the Cincinnati-Algonquin arch, here developed to the east of its present-day position.

The known Beekmantown sediments of the region are almost wholly carbonates, and dominantly are dolomites. A band higher in its proportion of limestone crosses southeastern Pennsylvania. In central Pennsylvania the carbonates are about three-quarters dolomite, about one-quarter limestone; the dolomites however consist of medium-magnesian rather than high-magnesian rocks, and so could be termed magnesian limestones.

Limestones and dolomites are subequal in Vermont and northeastern New York, on the eastern and northern flanks of the Adirondacks. In western Ohio, the reported Beekmantown beds are dolomites.

As in the case of the Upper Cambrian sediments, the writer believes that the dolomite-limestone pattern of the Beekmantown deposits reflects the geography of sedimentation and not of more fortuitous post-depositional geologic activities. Role of the factors that may have controlled distribution of the facies remains, however, uncertain. In the Black River-Trenton sediments, relation of the dolomites to arches and to the margins of the Michigan basin suggest that the dolomites developed along areas of shoaling. In the Beekmantown sediments, however, flat-pebble or edgewise conglomerates, believed to have developed on tidal flats, are strikingly displayed in early Beekmantown limestones both in central and southern Pennsylvania. Salinity of the waters of deposition may for example be a vital factor, that may be affected in part by shoaling, but also in part by the current and temperature patterns and other geographic features of the ancient seas.

Detritals are strikingly subordinate in the Beekmantown sediments of the Pennsylvania-New York region.

Along the southern margin of the Adirondacks, the thin wedge-edge of the Beekmantown, locally termed Tribes Hill formation, contains some quartz sand presumably worn from the Adirondack area and possibly reworked from the Upper Cambrian.

More extensively than is now known, sands may have been reworked from Upper Cambrian strata exposed along the emergent Cincinnati-Algonquin arch, and carried into what now are subsurface parts of the Beekmantown of northwestern Pennsylvania and western New York. In well records, such sandy deposits would be classed as Upper Cambrian, for want of means of closer age identification. A thin sandstone member in the upper part of the Beekmantown in central Pennsylvania may represent a tongue of such reworked sands. It is, however, reasonably clear that the Upper Cambrian sandy strata could not have been greatly elevated in the Cincinnati arch area, or they would have suffered deeper erosion and would have left a more striking record in the Beekmantown sediments.

Along their most southeasterly crops in Pennsylvania, the Beekmantown limestones contain increased amounts of clay. They may largely have graded into a clay facies farther in this direction, and if so the clay beds may be represented within the metamorphic rocks known as the Wissahickon schist. Some shales with Beekmantown-age graptolites have been reported near Harrisburg, but their paleo-geographic relationships are still uncertain.

Oil and Gas Possibilities of the Lower Ordovician Beekmantown Sediments

The Lower Ordovician Beekmantown sediments of the Pennsylvania-New York region comprise a thick and extensive body of carbonate rocks, having definite possibilities of porous zones suitable for petroleum reservoirs.

In outcrops in Pennsylvania, the Beekmantown sediments dominantly are limestones in a belt crossing the southeastern part of the state, but largely consist of dolomites or dolomitic limestones along the Nittany Valley arch near the Allegheny Front (see Figures 9, 10). The dolomites appear to have more promise as reservoirs than do the limestones. It is likely that the dolomitic facies will persist through much of the subsurface extensions of the Beekmantown, in the general fashion illustrated in Figure 9.

Some layers of the Nittany dolomite formation of the lower half of the Beekmantown group of central Pennsylvania, contain numerous vug-type openings. Insofar as such openings are inherited

Figure 7.—Map showing progressive recession in areas of sedimentation from Upper Cambrian to Lower Ordovician Beekmantown and to Middle Ordovician Chazyan time. Widely spaced oblique lines show areas of Upper Cambrian sediments; horizontal lines show areas of Beekmantown sediments; closely spaced oblique lines show areas of Chazyan sediments.

Figure 9.—Preliminary isopachous and isolithic map of Lower Ordovician Beekmantown sediments, extended beyond area of Figure 9 by incorporating data from deep wells. Oblique brick-type pattern represents dolomites; horizontal brick-type pattern indicates limestones. Stippling along southern margin of the Adirondack area represents quartz sand of the thin Theresa dolomites; stippling in more westerly area suggests possibilities of lenses of quartz sand reworked from emergent Upper Cambrian of Cincinnati arch.

Figure 11.—Preliminary isopachous map of Middle Ordovician Chazyan sediments. Deposits of the eastern area are almost wholly limestones, except for the Normanskill shale of the Taconic slices near Albany in eastern New York. In Michigan, some of the marginal area of the St. Peter sandstone, of presumed Chazyan age, is indicated by stippling.

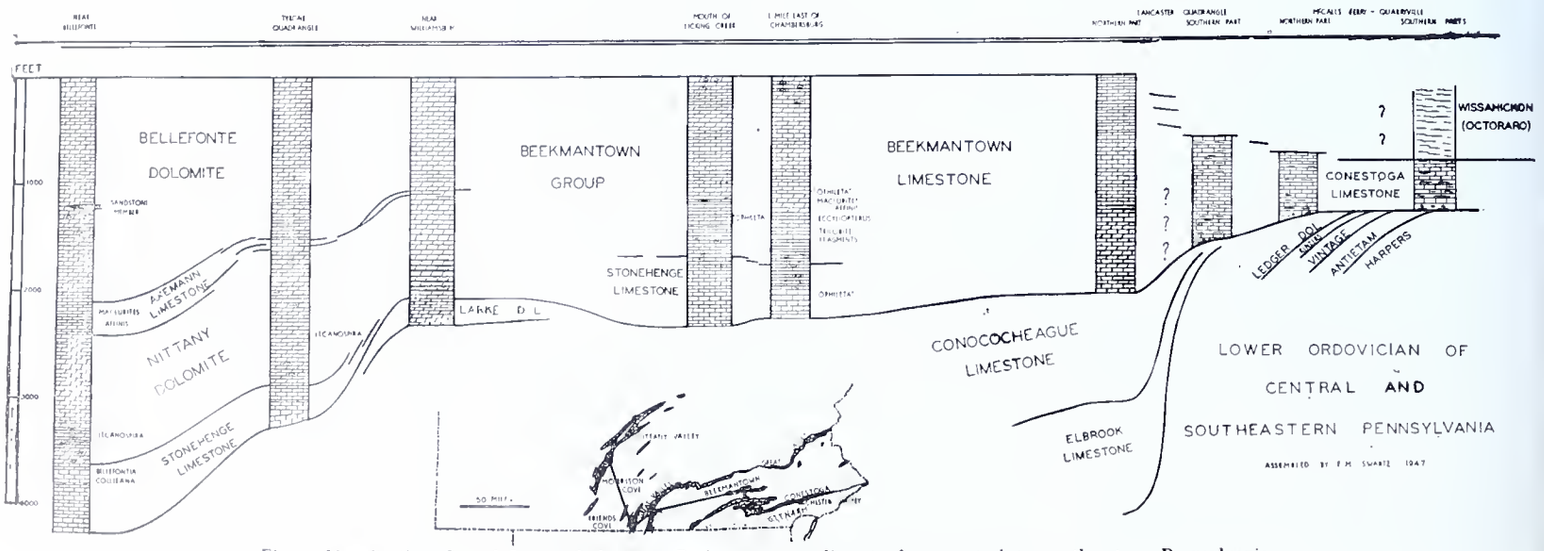

Figure 10.—Stratigraphy of Lower Ordovician Beekmantown sediments from central to southeastern Pennsylvania. True scale of convergence is shown by digram at top of figure.

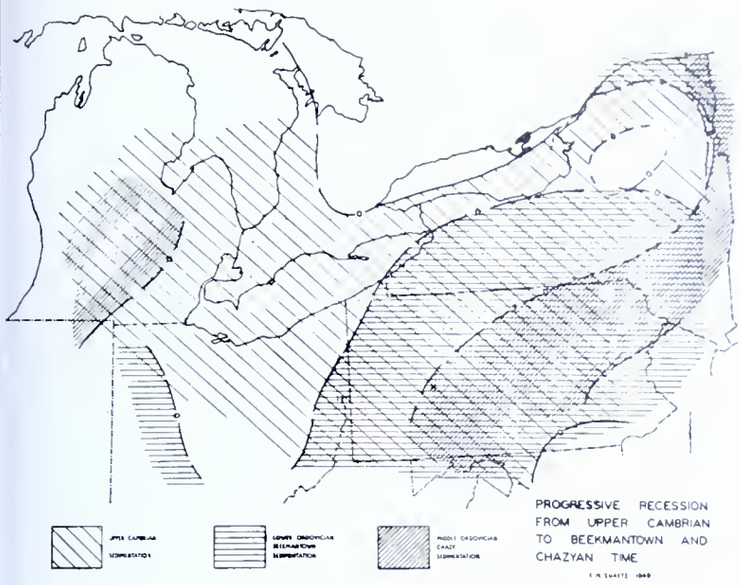

Figure 7

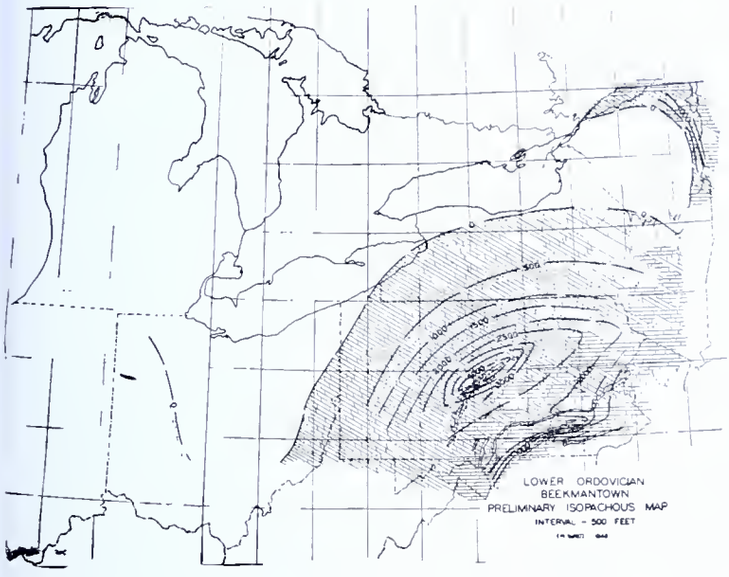

Figure 9

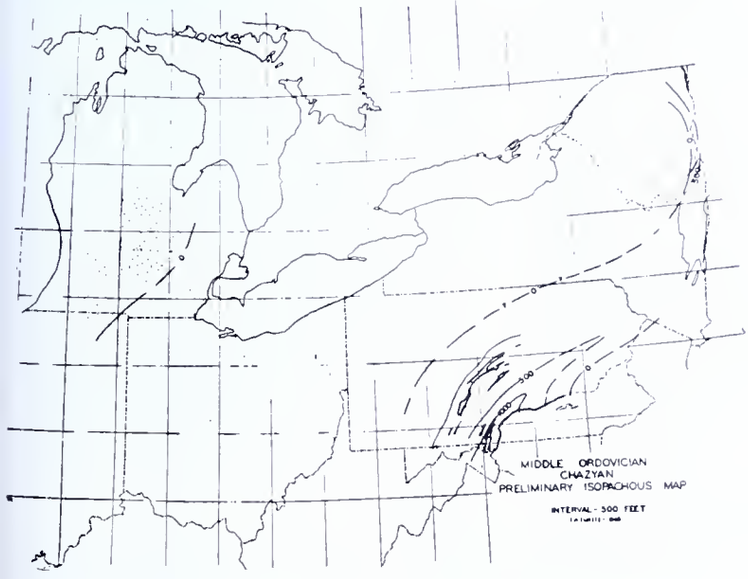

Figure 11

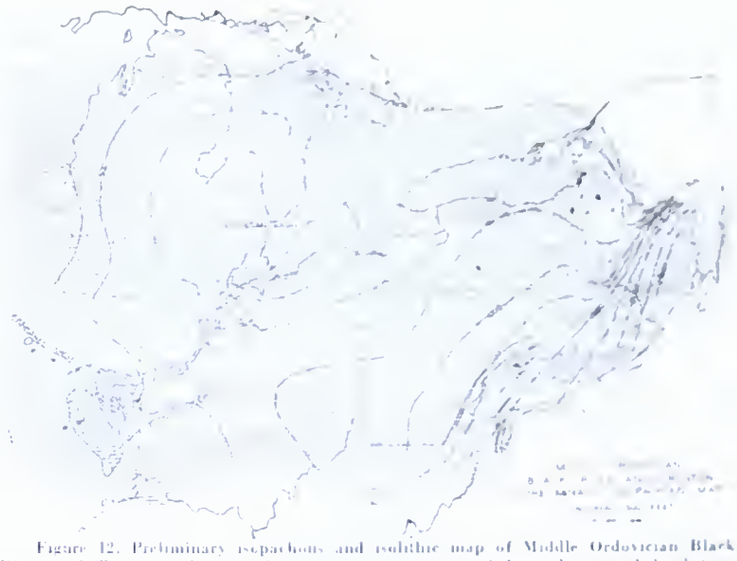

Figure 12. Preliminary isopachous and isolithic map of Middle Ordovician Black River and Trenton sediments. Limestones are represented by a horizontal brick-type pattern, dolomites by an oblique brick-type pattern, shales by horizontal lines. Trenton limestone oil pools are shown by closely spaced, parallel oblique lines, gas pools by stippled areas.

Figure 13. Map showing transgression of area of Middle Ordovician Black River-Trenton sedimentation, over recessive Chazyan basins.

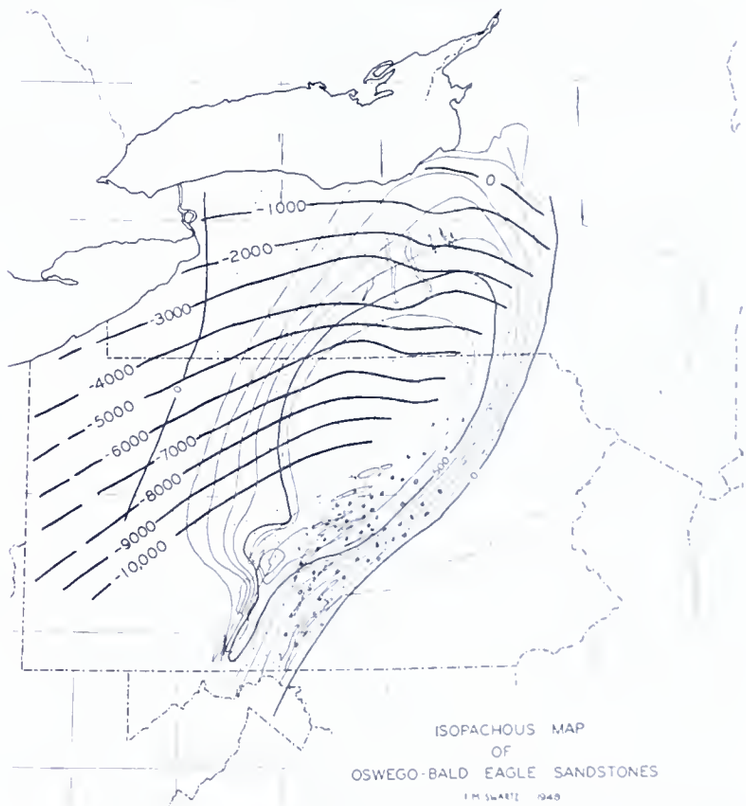

Figure 16. Preliminary isopachous, isolithic and structural contour map of Upper Ordovician Oswego-Bald Eagle sandstones.

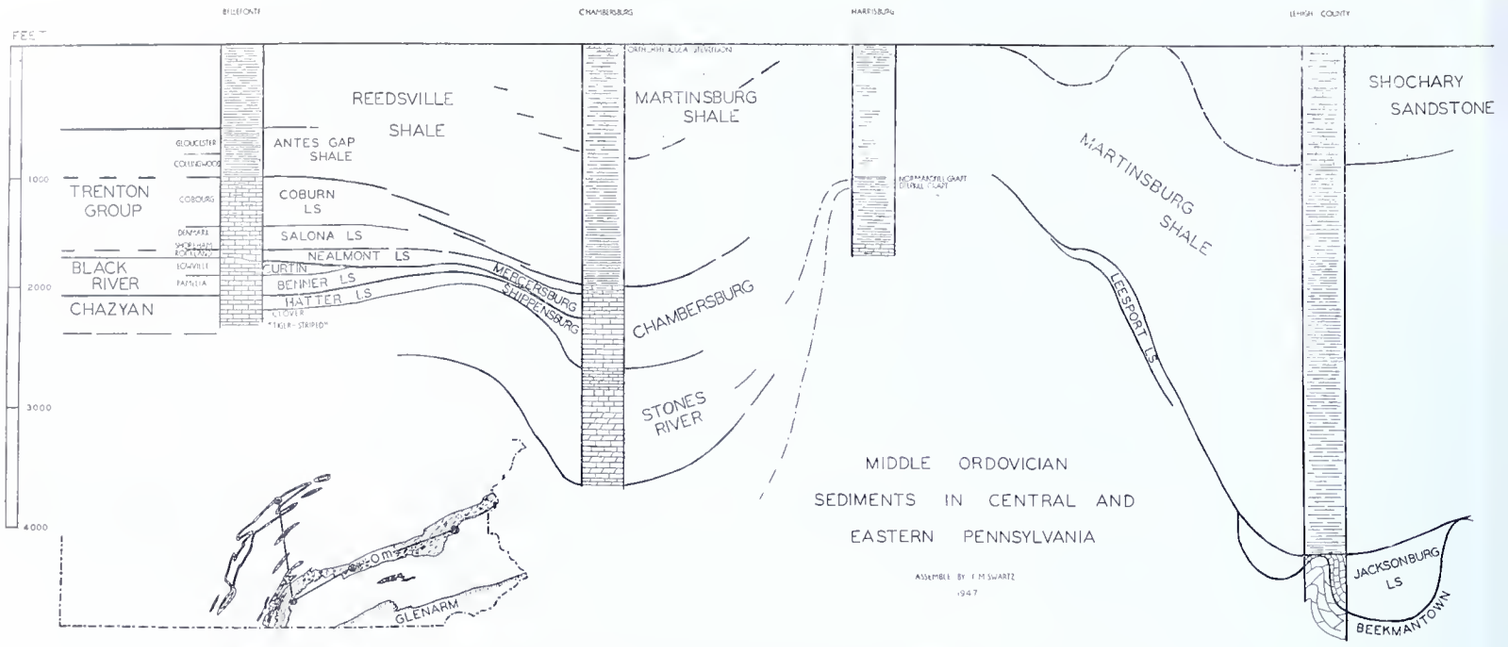

Figure 14. Stratigraphy of Middle Ordovician Black River and Trenton limestones, and of Middle and Upper Ordovician shale formations, along line from central to eastern Pennsylvania.

from early stages of the rock's history, they are a promising source of reservoir porosities, especially in more crystalline varieties of the dolomite where permeability is somewhat enhanced. Cavities in some outcropping ledges, however, contain residues suggesting that part, at least, of the openings have been enlarged by modern weathering.

Finer textured dolomites of the Beekmantown sequence, especially beds of the Bellefonte formation as seen in central Pennsylvania, are commonly traversed by many joints, giving possibility of late-stage porosity. Early-stage porosity such as that possibly represented in the Nittany, has more promise for oil and gas in the Beekmantown as a whole, even if jointing has favored some redistribution.

Other possibilities of early-stage reservoir porosity in Beekmantown sediments, are afforded by the chance that sand lenses were produced in northwesterly marginal areas by reworking of Upper Cambrian sediments exposed in the Cincinnati arch region. (See Figures 7, 9). Furthermore, the northwestward thinning and eventual disappearance of the Beekmantown should be related to unconformities that may locally have increased leach-porosities in some of the dolomite beds.

The Beekmantown sediments, like the other Cambro-Ordovician strata of the region, developed during the course of Paleozoic sedimentation a northwesterly rise in northwestern Pennsylvania and western New York. This rise favored northwesterly migration of oil and gas, within the realms of any permeable zones, provided the dip was not locally reversed by arches.

Subsurface portions of the Beekmantown dolomites thus give considerable promise of porous and permeable zones potentially suitable as petroleum reservoirs, and appear to include some of the more likely horizons for oil and gas occurrence, when comparisons are being made with other of the Cambro-Ordovician sediments of the region.

Relation to possible petroleum source beds is less readily judged. However, the Beekmantown sediments as a whole are marine sediments, and are underlain by marine sediments.

Prediction of details of geographic position of porous zones favorable for petroleum accumulation is insecure. Unconformities favorable for leach-zone porosities are increasingly developed toward the northwest, but the section is thicker in the neighborhood of the Allegheny Front and of Nittany Valley. If there was early-stage arching, local lifting of the surface during emergent stages would have favored local deepening of weathered zones.

Possibilities of porous sands reworked from Upper Cambrian exposures of the Cincinnati arch, should improve in northwesterly parts of the Beekmantown.

Distribution of any vug-type cavities that developed in the course of Beekmantown sedimentation, is not understood. The known vug-type openings in Nittany Valley are of course found in the area of thickest Beekmantown deposits, not toward the thinned margins.

Depth of the Beekmantown through most of its area of subsurface occurrence northwest of the Allegheny Front, is an important hindrance to exploration. At the Front, the depth may be around three miles. As far west as the Hockenberry well in western Pennsylvania, the top of the Beekmantown dolomites is 9,558 feet below the surface; at the Arcade No. 1 well in western New York the depth is 6,121 feet.

Middle Ordovician Chazyan Sediments

Recession of the Appalachian seaways that marked Early Ordovician Beekmantown as compared to Upper Cambrian sedimentation, progressed still farther during Middle Ordovician Chazyan time. Accordingly, Chazyan limestones are restricted to a belt of moderate width crossing central Pennsylvania and extending northeastwards into Vermont and St. Peter sandstones of supposed Chazyan age extend westwards from a line crossing southeastern Michigan and Indiana. Thus the general Cincinnati arch region was broadly emergent, and its land surface connected eastwards with the gently upwarped Adirondack area. (See Figures 7, 11.)

In southcentral Pennsylvania, the Chazyan limestones attain thicknesses as great as 1,000 feet or slightly more. The axis of greatest thickness apparently extends northeastwards into the subsurface area of northeastern Pennsylvania, and thence across southeastern New York to the type area of the New York-Vermont border, where thicknesses of nearly 1,000 feet are recorded.

Along the outcrop belt in eastern Pennsylvania, the Chazyan limestones thin and then disappear by unconformity. Along the Nittany arch in central Pennsylvania, the limestones are thinner than in the southcentral part of the state. Chazyan sediments are absent according to Fettke in the Hockenberry and Childs wells of western Pennsylvania, and in the Arcade well in western New York.

Much farther to the west, parts of Michigan and Indiana are underlain by easterly marginal portions of the St. Peter sandstone.

The Chazyan limestones of the easterly belt contain small amounts of detrital materials, mostly as impurities in the limestones rather than as separate bodies of sandstone or shale. Thin sandstone members occur near the top and base of the Chazyan sequence in Vermont. There are subordinate beds of dolomite or magnesian limestone both in Vermont and Pennsylvania.

In the westerly area, the St. Peter formation is noted for its clean quartz sands with rounded and well-sorted grains.

Widespread disconformities are associated with the Chazyan sediments. Judg-

ing from present knowledge, much of central and western New York, western Pennsylvania, and all of Ohio and southwestern Ontario were emergent during Chazyan time. Emergent surfaces must have stood at low altitudes, or more detritals would have been reworked and carried into the eastern Chazyan basin. In Michigan, the St. Peter sandstone was deposited on a surface of gentle relief, with 100-foot to 300-foot valleys cut by erosion into Upper Cambrian sediments. Disconformities probably are associated with limestones of the easterly Chazyan trough, but are not well understood. The easterly areas of Chazyan limestones shown in Figure 11 probably represent about the maximum limits of submergence, and in part probably lifted above water level during portions of Chazyan time.

Oil and Gas Possibilities of the Middle Ordovician Chazyan Sediments

The Middle Ordovician Chazyan sediments of the Pennsylvania-New York region do not of themselves have much promise for oil and gas occurrence. The Chazyan sediments are comparatively limited in geographic extent; where present they generally are a subordinate member of a thick limestone-dolomite sequence, without discernible special promise as compared to others of the carbonate formations.

The Chazyan emergence does have interest as a possible source of reservoir porosities.

Portions of the Beekmantown and Upper Cambrian sediments exposed during Chazyan time across central and western New York, western Pennsylvania, Ohio and southwestern Ontario, may where sufficiently elevated have undergone weathering favorable for forming reservoir-type solution porosities. Early-stage arches if present would offer likely loci for such leaching. The Chazyan geography may have caused some reworking of quartz sands from the Upper Cambrian sediments, that seem to have been broadly exposed in Ohio and southwestern Ontario during Chazyan time.

Middle Ordovician Black River And Trenton Sediments

The comparatively restricted basins within which the Chazyan deposits accumulated, gave place by marked broadening to the subsidence, submergence, and sedimentation of Black River and Trenton time. (Compare Figures 11, 12, 13.) Part of the Adirondack region may have remained emergent; otherwise during much of the Black River and Trenton intervals, marine waters flooded virtually all of Pennsylvania, New York, Ohio, southeastern Ontario, and Michigan, inundating the Cincinnati arch that had been so broadly upwarped during the preceding Beekmantown and Chazyan stages. This flooding must not, however, be regarded as continuously covering the entire area; instead, evidence can be found of a number of fairly widespread withdrawals of the sea, especially in Black River time.

A further major change was initiated during Trenton sedimentation. Easterly land surfaces became extensively emergent, and began to undergo the deformation that raised the ancient Taconic Mountains, now evidenced in the east by their truncated folds and faults, and in central Pennsylvania and central New York by the thick and coarse detritals supplied by their vigorous, Ordovician erosion. Until the end of Trenton time, however, the detritals that reached the Pennsylvania - New York areas were mostly fine-grained, and in large part were deposited along easterly portions of the platform of sedimentation. (See Figures 13, 14.)

The Black River-Trenton sediments of the Pennsylvania to Michigan region dominantly are carbonates. Lime deposits, including shelly coquinas as well as chalky flocculates, accumulated across central and western Pennsylvania, central and western New York, southwestern Ontario, and central and northern Ohio, into the downwarping area of the Michigan basin.

In northwestern Ohio and in Indiana, along and to the west of the present-day Cincinnati or Findlay Arch and along the Kankakee arch, as well as along the western and northern margins of the Michigan basin, the widespread Black River-Trenton limestones give place progressively to dolomites and limestones and in some areas to dolomites with little limestone.

Relation to the structural axes has led some geologists to conclude that the dolomites are secondary in origin with dolomitization conditioned at least in part by folding. It has also been suggested that dolomites along the oil-producing belts in Ohio and Michigan originated from solutions enriched in magnesium during ascent through subjacent Early Ordovician and Upper Cambrian strata. However, both the geography of the Black River-Trenton dolomites, and analogy with dolomites of the Early Ordovician and Upper Cambrian observed in central Pennsylvania, seem to the writer to favor the hypothesis that much of the dolomitization was accomplished while the deposits were relatively fresh on the sea floor if not during actual sedimentation. In this case, the geography suggests that shoaling was in some fashion a factor in the dolomitization, though its tendency to favor dolomitization presumably stemmed in some way from effects on chemistry of the sea water in contact with the sediments.

It is recognized that caution must attend any attempt to generalize from presumed conditions of dolomitization in Pennsylvania to problems of dolomitization elsewhere. The suggestion that dolomitization in the Trenton of Ohio may have been essentially concurrent with sedimentation, is a working hypothesis that needs investigation by studies of carbonate rocks in that region.

Members of the Black River and Trenton limestones vary greatly in purity. Subordinate clayey fractions of the Trenton limestones of central Pennsylvania evidently were brought in from easterly lands. Authigenic quartz crystals probably built upon silt fragments, and rarer authigenic feldspar crystals, contribute to impurities of some Black River limestone beds. Falls of volcanic ash occur as widely traceable interlayers in both Black River and Trenton formations. Comparatively thin and lenticular members of the Black River sequence are extraordinarily pure in central Pennsylvania, and locally occur as mineable beds containing less than 2 per cent of substances other than calcium carbonate.

Turning again to the detritals that spread during Trenton time into Pennsylvania and New York, the correlations illustrated in Figure 14 indicate that clays appear at geologically earlier levels on the east, and carbonates persist to higher horizons on the west. Progressive westerly spreading of the clays reflects continued rise of the easterly, eroding lands, abetted by strengthening currents in shoaling waters of the region of sedimentation. So far as known, significant bodies of land-derived sands did not accumulate in Pennsylvania and New York during Black River and Trenton time, except possibly in areas east of preserved strata recognized as belonging to these ages. Lime sands, formed by fragmentation of shells and perhaps of other lime materials, can be recognized in various cross-bedded Black River layers.

As contoured in Figure 14, the Black River-Trenton sediments vary rather gradually in thickness. The Michigan basin was a subsiding area, the sediments thickened probably because of greater continuity of sedimentation. The thinned belt that extends about along the course of Lake Erie, may represent an easterly Black River-Trentonian version of part of the Cincinnati arch. Another axis of thinning that projects southwestwards from the Adirondacks, has been termed the Adirondack line by Kay, and has been interpreted as an axis of shoaling that tended for a time to bar the westward spreading of clays of the deeper easterly waters. Marked thickening east of the Adirondack line reflects rapidity of deposition of clays and silts brought in from the easterly, rising lands. Problems about correlation of some of the easterly shales results in uncertainties about true values of the easterly thicknesses.

Oil and Gas Possibilities of the Black River and Trenton Sediments

Virtually all of the oil and gas production obtained to this date from Cambrian and Ordovician strata in and near the northern portion of the Appalachian basin, has come from Trenton sediments.

In New York, gas has been obtained in commercial quantities in the Trenton limestones in a number of small fields near the eastern end of Lake Ontario. Production is scattered irregularly through a gross thickness of about 600 feet of strata. The rock consists of dark

gray limestone with some thin interbeds of dark gray shale. The gas apparently occupies systems of coarse openings, capped by the shale breaks, and not effectively connected over very large areas. Open flows of several wells have been estimated at one to several million cubic feet per day, with high initial gas pressures. Such large flows are very short-lived.

By far the largest Trenton production of the general region has come from the Lima - Indiana field extending across northwestern Ohio into Indiana. About 480,000,000 barrels of oil have been recovered. The oil comes from at least three dolomitized zones of the Black River-Trenton sequence, the most productive zone being in the upper 50 feet of Trenton limestone-dolomite strata.

Across northwestern Ohio, the Lima oil fields roughly parallel but lie northwest of the present Cincinnati or Findlay arch. Dolomite fragments from the producing zones are irregularly porous, with openings ranging from pin-sized pores to cavities as much as an inch or more in diameter.

Gas replaces oil southwestwards in Indiana along the trend of the Lima fields, rather than eastwards across the trend as occurs in the Upper Devonian fields of Pennsylvania.

Essential parallelism of the Lima oil belt with the axis of the Findlay arch, suggests a relationship of cause and effect. Various changes in thickness of Cambrian and Ordovician formations as they cross the general region of the Cincinnati-Findlay arch, indicate that the structure was weakly active during Cambrian and Ordovician time, and that the crest shifted widely in geographic location in successive periods. It is possible that the Lima fields roughly mark the position of the crest-region as developed in Trenton time. Porosity might then have been favored by sedimentation processes of the shoaled waters, though it more likely may have resulted from leaching along the arch during temporary stages of emergence.

Small, additional Black River-Trenton oil and gas fields have been discovered in northwestern Ohio, northeastern and northwestern Indiana, southern Michigan, and southwestern Ontario. In many of these fields, the producing horizons are dolomites.

Subsurface extensions of the Black River and Trenton sediments remain unexplored over large areas in and near the northern portion of the Appalachian basin.

In western Pennsylvania, only three wells have reached Trenton-Black River strata, and only a few wells have been drilled to these rocks in the southern half of western and central New York. In Ohio, wells drilled to the Trenton beds are located 75 miles and more to the west of the Pennsylvania line, except in the northernmost tier of counties.

The Black River and Trenton strata of these untested areas are not exceptionally promising, so far as can be judged from present knowledge. There is no present evidence that extensive dolomitized zones can be expected, and significant quartz sands almost certainly are lacking. Shaly breaks such as those that trap gas accumulations in small fields of central New York, should occur in the upper limestones over large areas. The gentle warping and emergence found at the top of the Black River limestone in central Pennsylvania, may persist toward the northwest and may occasion some local solution porosities.

The Black River-Trenton rocks do, it is true, represent the highest part of a thick carbonate sequence, in which porosities may today exist as joints and other fractures, together perhaps with minor solution openings; in the past and especially during Paleozoic time, this thick limestone sequence is likely to have yielded significant quantities of petroleum. Since virtually the beginning of their history, the Trenton carbonates have been capped by thick Upper Ordovician clayey sediments, that must have interfered with upward escape of oil or gas.

Through their unexplored areas, the Black River-Trenton carbonate rocks appear to be favorably situated with respect to promising petroleum source beds and relatively impermeable cap rocks. Potential reservoir porosities are less promising.

Middle Ordovician-Late Ordovician Shale Formations

The shale formations included by Kay in the upper part of the Middle Ordovician Trenton group in central Pennsylvania and central New York, are overlain without marked boundary by other shales classed as Upper Ordovician by all workers in the region.

The Middle Ordovician-Upper Ordovician shale sequence above the limestones totals about 1,000 to 1,200 feet in central Pennsylvania (see Figure 13), and is similar in thickness in the Trenton Falls-Watertown area southwest of the Adirondacks in central New York.

The lower shales in both regions are fine-grained clay shales, generally dark with organic materials, and probably somewhat calcareous when fresh. Silt appears in overlying parts of the shales, and some fine-grained sandstones are interbedded in the highest portion.

The shales variably contain fossil graptolites, brachiopods, mollusks, and trilobites. They were deposited by marine to somewhat brackish waters.

Eastwards in both New York and Pennsylvania, shales appear at progressively lower levels in the Middle Ordovician, and sandstones are increasingly prominent in the highest beds.

In their subsurface extensions across western New York and western Pennsylvania, the Middle Ordovician - Late Ordovician marine shales maintain a comparatively uniform thickness, although the lower and upper boundaries may both change somewhat in age. In general, the expected westerly decrease seems to take place in the silt and sand fractions of the rock.

In much of Ohio and southwestern Ontario, there is a marked progressive change in the summit of the marine shaly beds, so that in parts of these areas as well as in Michigan, marine shaly strata continue into the highest Ordovician.

Oil and Gas Possibilities of the Middle Ordovician-Late Ordovician Shale Formations

The Middle Ordovician-Late Ordovician shale formations of the Pennsylvania - New York - Ohio area offer in themselves little promise of oil and gas occurrences. They are however of interest in interpretation of oil and gas possibilities of the region not only because they have served as a barrier to escape of the petroleum of underlying strata, but also because they may have been the source beds of significant amounts of petroleum. If so, it is likely that most

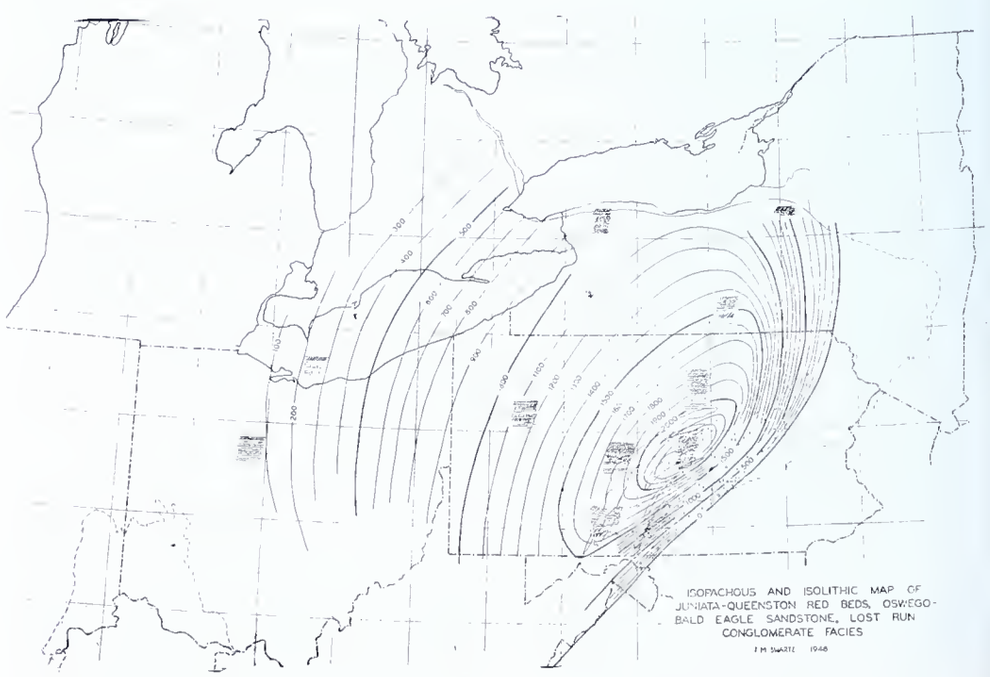

Figure 15. Isopachous map of the Upper Ordovician gray sandstone-red bed sequence. Columnar sections illustrate local details of the rock succession. Sands are indicated by stippling, gravels by small circles, shales by lines paralleling the general bedding; an overlay of oblique lines indicates that the sediments are red-colored.

of their available petroleum was forced from them long before the close of Paleozoic sedimentation.

Sandstones that in the past at least had possibilities as oil and gas reservoirs, are interbedded in the upper part of the shale sequence in central to eastern New York and in east-central to eastern Pennsylvania. These sandstones in part are themselves marine to estuarine, and are intimately associated with marine to estuarine shaly layers. In their regions of thickest development, the sandstones tend to be beveled by an erosional unconformity, that cut deeply into their anticlinal structures, and that may have allowed escape of much of their earliest-stage petroleum accumulations. (See Figure 13.) In eastern Pennsylvania, the formations have been so strongly deformed that portions of the clayey members today are slates, reducing the likelihood of retention of oil or gas that may formerly have collected in the sandstone interlayers.

Upper Ordovician Gray Sandstones and Red Beds

In western New York and in central Pennsylvania, the Upper Ordovician shale formations are in general overlain first by gray to greenish sandstones and then by red sandstones and silty shales, likewise classed as Upper Ordovician by most geologists. These rocks in combined sequence reach their greatest thickness of around 2,200 feet in central Pennsylvania, well to the east of the Allegheny Front. (See Figure 15.) An axis of maximum thickness extends in a curving line northwards and southwestwards.

Eastwards from the axis of maximum thickness the sequence thins rapidly and disappears by unconformity in eastern Pennsylvania and eastern New York. In this thinning marginal area, the sediments tend to coarsen, and transgress upon a surface of unconformity eroded toward the east into the subjacent, folded shales.

Westward from the area of maximum thickness, thinning is comparatively gradual. Across western Pennsylvania and western New York, the thinning in part reflects slower sedimentation, but in larger part results from lateral change of basal grayish sandstones which become finer grained and then pass into gray shales. In southwestern Ontario and in Ohio, gray shales with some interbedded limestones progressively replace the red shales, until finally the last tongues of the gray sandstone-red bed facies-complex have disappeared.

In New York, the gray sandstone formation is named Oswego from a town on the southeastern shore of Lake Ontario, and the overlying red beds are termed Queenston from a village near Niagara Falls. In central Pennsylvania, the red beds are known as Juniata formation; the gray sandstones are variously classed as Oswego formation on the supposition of subsurface continuity with the type Oswego of New York, and by the local name Bald Eagle sandstone in recognition of geographic changes.

The Juniata beds in central Pennsylvania include in their lower part medium-grained, red-colored sandstones. There are red silty shales or siltstones and interbedded sandstones in the upper half, with red quartzitic sandstones at the summit. The underlying Bald Eagle or Oswego sandstones are 600 to 700 feet thick along much of the Allegheny Front. The sandstones of both the Juniata and Bald Eagle formations are mostly graywackyish, with chloritic fractions that tend to be squashed into the interstices. Many sandstone layers in both formations contain numerous disseminated crystals of iron carbonate that enclose sand grains and likewise help to block interstices.

Traced eastwards in central Pennsylvania, the middle and upper parts of the gray Bald Eagle sandstones become increasingly conglomeratic, and are separable as a distinct conglomerate formation, underlain for some distance by gray sandstones of Bald Eagle facies. Farther east, where the gray sandstones-red beds facies transgresses unconformably upon the subjacent shale formations, the basal conglomerates probably become transgressively younger.

The gray sandstone formation in central Pennsylvania lacks known fossils; fossils are unknown in the Juniata red beds except for tubular **Scolithus** structures believed to represent worm tubes. The red beds probably are fresh water sediments; the gray sandstones may have been spread by freshened brackish if not truly fresh waters.

In New York, the Queenston red beds in their more westerly type area contain less sandstone than does the Juniata of central Pennsylvania; they lack fossils except for **Scolithus** tubes. Traced northwestwards in Ontario, gray interbeds appear containing marine fossil faunas distinctive of the Richmond group of Indiana.

The Oswego sandstone beds at Oswego are graywackyish, unfossiliferous. Fossiliferous, in part dolomitic sandstones included in the lower half of the Oswego in neighboring areas, might well be classed in a distinct, subjacent formation. Some beds of the unfossiliferous sandstones contain disseminated crystals of iron carbonate. The gray sandstone sequence thins westwards, becomes finer grained as it grades laterally into shales and disappears near the eastern shore of Lake Erie.

Oil and Gas Possibilities of the Upper Ordovician Gray Sandstones And Red-Bed Sequence

The red-bed sandstones, shales, and siltstones at the summit of the Ordovician in central and western Pennsylvania and central and western New York, probably are mostly fresh water sediments without significant accumulations of oil or gas. The underlying grayish sandstones, on the contrary, are believed to merit investigation, especially in their more westerly portions where they increasingly intergrade with marine shales, are probably themselves in part marine, may have been better winnowed, and perhaps have suffered less from the combined effects of load and deformation.

A preliminary map of the geographic distribution and thickness variations of the grayish Oswego-Bald Eagle sandstones is reproduced in Figure 16, together with generalized structure contours on the upper surface. This figure is based on a map originally prepared on behalf of the Quaker State Oil Refining Corporation and Bradley Producing Corporation, and is here published with permission of officers of the companies.

The grayish sandstones and the conglomeratic beds into which they pass on the southeast, reflect the uplift and consequent vigorous erosion of easterly hilly if not mountainous lands, together with westward retreat of the marine waters that had covered much of Pennsylvania and New York during preceding portions of the Ordovician.

The gray sandstones, though they in general lack marine fossils in the areas of outcrop, are intimately related to the thick, underlying marine shales, and pass toward the west into marine shales, probably themselves becoming marine for the most part as this change progresses. Like the oil-bearing sandstones of the Upper Devonian of Pennsylvania, they are associated with westerly regression of marine waters, and westerly shift of the areas of sedimentation of sandy detritals.

Samples of the grayish sandstone from some exposures in central Pennsylvania, have porosities measuring less than 4 per cent. Where penetrated by numerous wells in central New York within 50 miles of the belt of outcrop, the sandstones according to published logs have rarely yielded any fluids, suggesting that here again porosity and permeability in general are low.

Although available data about porosity and permeability are unencouraging in central Pennsylvania and in wells near the outcrop in central New York, porosity conditions may improve in more westerly portions of the gray sandstones. In shoaled areas, that shifted position along the margins of the marine waters, parts of the sands may have been better winnowed by surf and currents than were most of the sandy materials on the east, and post-depositional compaction and cementation may be less extreme. Furthermore, some early-stage petroleum accumulations may have maintained local reservoir conditions by impeding cementation and loss of porosity.

Few wells have reached the westerly portion of the Oswego sandstones. The only well that has penetrated the formation in western Pennsylvania is that recently drilled near Tally-Ho; farther west at the Childs and Hockenberry wells the sandstones are wanting because of change to shale. In New York, the westerly Oswego was penetrated many years ago by the deep Depew and Rochester wells, and has been reached more recently by the Arcade and Herrington

wells. A small amount of water entered the Tally-Ho well at or near the level of the Oswego. The results of these few wells have been negative, but they do not adequately test the possibilities of the westerly part of the Oswego.

Summary of Tentative Views About Oil and Gas Possibilities of Cambrian And Ordovician Sediments of the Pennsylvania-New York Region

The Cambro-Ordovician strata of the Pennsylvania-New York region include thick marine-estuarine sand, clay, and carbonate sequences such as are productive in other areas of the continents. It is reasonably probable that petroleum developed in these rocks during past geologic stages. The fundamental problem appears to be: Have significant quantities of oil and gas been preserved, and if so, where?

It is likely that much of the petroleum of the region entered first-stage reservoirs during Paleozoic time. Time of development is significant because conditions then existing controlled early migration, entrapment, and loss, and thus affected possibilities both of retention in early loci and of movement to later, modified reservoirs. Where petroleum saturated openings in the rock, cementation was hindered and the existing porosity tended to be preserved. Possibility of local preservation of porosity is significant in relation to very low porosity values found in surface crops of such strata as the Oswego-Bald Eagle sandstones.

Localization of early-stage reservoirs was affected by both original and secondary developments in porosity, permeability, and structure. Stratigraphic studies aid investigation of these basic features by relating trends in facies and textures to the geography of sedimentation; by revealing surfaces of unconformity with which leach-zones may be associated; by giving evidence about convergence and warping or arching of the platform of sedimentation, that modified early structures of the strata.

Geographies of thickness and facies trends of each of major subdivisions of the Cambro-Ordovician sediments are illustrated by the accompanying isopachous and isolithic maps. Unconformities are especially associated with the progressive recession of areas of sedimentation from Upper Cambrian to Beekmantown and to Chazyan time. Convergence of the Paleozoic sediments across northwestern Pennsylvania gives evidence of early development of northwesterly rise of the sediments and thus of one element of warping of the platform; early-stage arching within the arch of the platform is possible but is not well substantiated.

Effects of Late Paleozoic Appalachian deformation on oil and gas accumulations, are not well understood. In parts of southeastern Pennsylvania, metamorphism is advanced and must have dispersed any early-stage petroleum accumulations. In detail, however, suppositions about occurrence based on the carbon-ratio theory appear to need modification.

In the Cambro-Ordovician sediments of the Pennsylvania-New York region, parts of the Upper Cambrian, Beekmantown, and Oswego sediments offer possibilities of reservoir porosities, and the shale-capped Trenton limestones have at least some promise. Geographies of the sediments of each of these rock divisions are discussed under appropriate headings of the report, and oil and gas possibilities are considered in preliminary fashion.

Through much of their subsurface areas in Pennsylvania and New York, the Cambro-Ordovician sediments occur at depths that will make exploration very costly. Subsea depths of the Upper Cambrian sandy dolomites and Upper Ordovician Oswego sandstone are indicated in Figures 5 and 16, respectively.

Exploration of Cambro-Ordovician strata has been very limited in Pennsylvania and New York. Further prospecting deserves consideration on a high-risk basis.

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